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PROCEEDINGS

of the

Michelson Meeting

of the

OPTICAL SOCIETY OF AMERICA

The Michelson Meeting

of the

OPTICAL SOCIETY OF AMERICA

and

Optical Exhibition

at the

NATIONAL BUREAU OF STANDARDS

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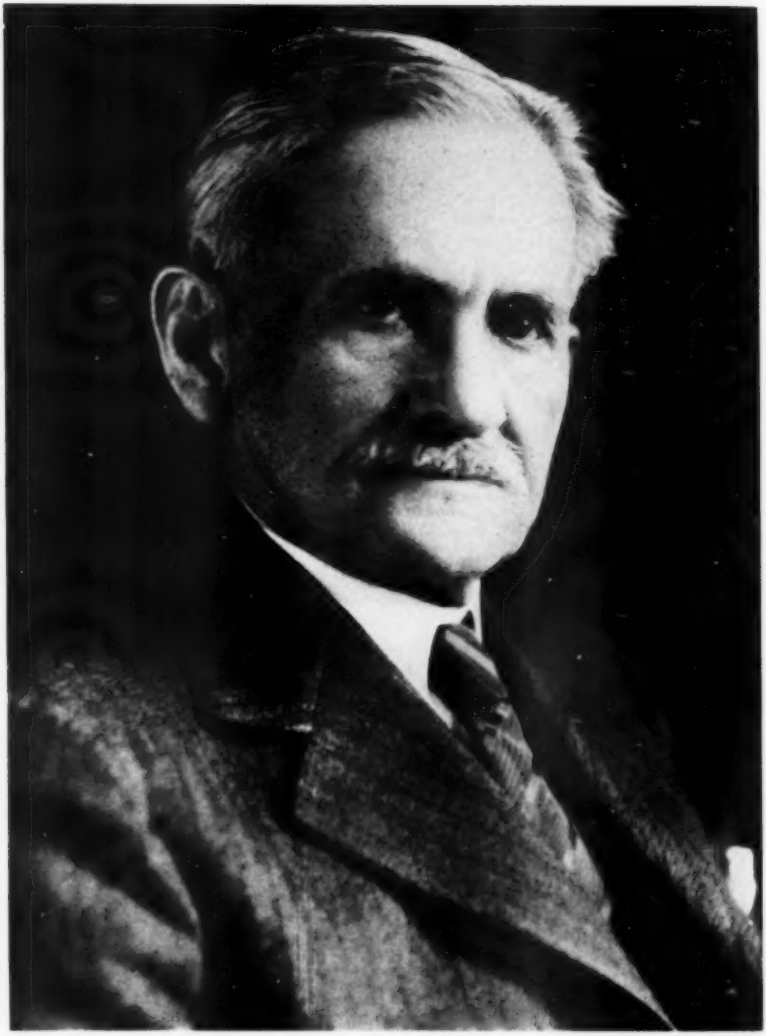


Albert A. Michelson at the Michelson Meeting, 1928

This Meeting is Named in Honor of

Albert A. Michelson

In Celebration of

The Semi-Centennial of the

Publication

of his

FIRST COMMUNICATION ON THE VELOCITY OF LIGHT

(Silliman's Journal, *15*, p. 394; 1878)

and

In Appreciation of

His Preeminent Contributions to Optics

Extending Over Half a Century:

1878 Method for measuring the velocity of light.
1879 Determination of the velocity of light.
1881 First experiments on ether drift.
1882 The Michelson interferometer.
1884 Measurement of the velocity of light in water and carbon disulphide.
1886 The influence of the motion of the medium on the velocity of light.
1887 The Michelson-Morley experiment on ether drift.
1891 Measurement of Jupiter's satellites by interference.
1892 The visibility of interference fringes—homogeneity and fine structure of spectral lines.
1893 Comparison of cadmium wave lengths and the length of the international meter.
1897–1898 Separation of the components in the Zeeman effect.
1898 Harmonic analyzer.
1900 The echelon spectroscope.
1913 Analysis of sun-spot cycle.
1914 Measurement of the rigidity of the earth—revealing earth tides.
1915–1916 Ruling, testing, and performance of a 10-inch diffraction grating.
1921 Measurement of the diameter of α-Orionis with interferometer.
1924 New measurements of the velocity of light.
1925 Effect of earth's rotation on the velocity of light.
1928 Repetition of the Michelson-Morley experiment.

A. A. Michelson.

Albert A. Michelson at the U. S. Naval Academy, 1873

THE OCCASION OF THE MICHELSON MEETING*

At the recent meeting of the American Chemical Society, President Parr said: "It is obvious .... that somewhere along about fifty years ago we might properly draw a dividing line between the old order and the new. It was the starting point of a new period when the investigational type of procedure in all scientific lines was taking on new life and unprecedented activity." The late seventies of the past century were indeed marked by memorable events which have been celebrated with public acclaim,—the invention of the phonograph, the telephone, and the incandescent lamp. We are met today to celebrate an event of this period of peculiar interest to us although it has made less appeal to the general public. We are celebrating the semi-centennial of the publication of Albert A. Michelson's first contribution to science,—his now famous method for measuring the velocity of light, contributed to Silliman's Journal when he was an ensign at the Naval Academy.

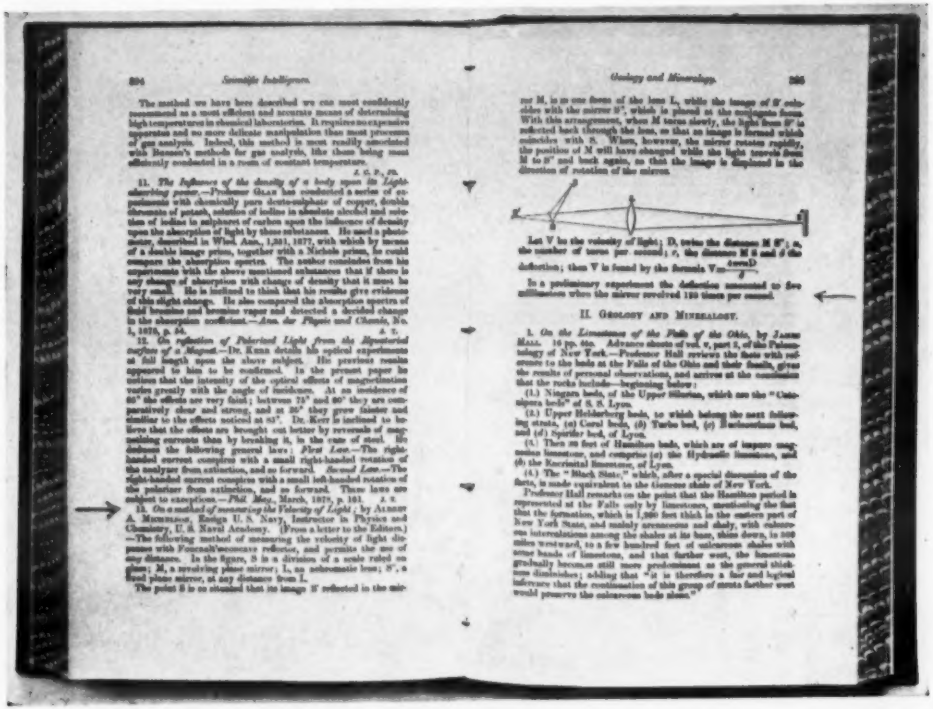
Man is wont to celebrate many divers anniversaries,—particularly births, and even deaths. It has always seemed to me quite inappropriate to celebrate the death of genius. But what of births? All men are born biologically; some lay claim to a second or spiritual birth; but to only a few is it given to be born intellectually in any very significant sense. It is such a rare and memorable event that we celebrate today,—the birth of Michelson as a man of science.

Fifty years of devotion to optics and most preeminent contributions to the cardinal facts of that science have made the name Michelson almost synonymous with optics; especially does it stand for accuracy in optical measurements.

We have named this the Michelson Meeting to mark our appreciation of the results of this half century of research in optics. We have formally dedicated this meeting to the honor of this veteran investigator and acknowledged dean of our science; we are making a newly compiled bibliography of his work a part of the proceedings of this meeting. It may seem to many of you that we might have done more,—we might have arranged a program of papers reviewing and appraising this work. It has however seemed to us that this might better be left to a centennial celebration after the present generation has passed; and we doubt not that our successors will hold such a memorial celebration. It is our good fortune to be of Michelson's own time; and we have desired to make this a more informal friendly occasion,—a genuine birthday

* Adapted from remarks made at the Meeting by the President of the Optical Society.

party for the honored guest. Our chief joy today is that Professor Michelson is himself with us and is contributing the outstanding paper to our program. Having evidenced in a simple way our appreciation and good will, it seems more fitting that we should now hold our peace and be ourselves instructed by what the veteran leader and guest of honor has to say. The occasions on which the torch of learning is passed on with the personal touch are of very real value to the advancement of science; many young men here present will doubtless recall twenty-five or fifty years from now the fond memory of the meeting at which they personally saw and heard Michelson. We have sought to honor Michelson; the truth is rather that by his presence here he both honors and inspires us.



The method we have here described we can most confidently recommend as a most efficient and accurate means of determining high temperatures in chemical laboratories. It requires no expensive apparatus and no more delicate manipulation than most processes of gas analysis. Indeed, this method is most readily associated with Bunsen's methods for gas analysis, the three being most efficiently conducted in a room of constant temperature.

A. G. P., Jr.

11. *The Influence of the density of a body upon its Light-absorbing power.*—Professor GLAN has conducted a series of experiments with chemically pure dextro-sulphate of copper, double ethereals of potash, solution of iodine in absolute alcohol and solution of iodine in sulphuret of carbon upon the influence of density upon the absorption of light by these substances. He used a photometer, described in Wied. Ann., 1,241, 1877, with which by means of a double image prism, together with a Nichols prism, he could compare the absorption spectra. The author concludes from his experiments with the above mentioned substances that if there is any change of absorption with change of density that it must be very small. He is inclined to think that his results give evidence of this slight change. He also compared the absorption spectra of fluid bromine and bromine vapor and detected a decided change in the absorption coefficient.—*Ann. der Physic und Chemie*, No. 1, 1878, p. 54.

A. S.

12. *On reflection of Polarized Light from the Equatorial surface of a Magnet.*—Dr. KERR details his optical experiments at full length upon the above subject. His previous results appeared to him to be confirmed. In the present paper he notices that the intensity of the optical effects of magnetization varies greatly with the angle of incidence. At an incidence of 85° the effects are very faint; between 75° and 80° they are comparatively clear and strong, and at 70° they grow fainter and similar to the effects noticed at 85°. Dr. KERR is inclined to believe that the effects are brought out better by reversals of magnetizing currents than by breaking it, in the case of steel. He endorses the following general laws: *First Law.*—The right-handed current conspires with a small left-handed rotation of the polarizer from extinction, and so forward. These laws are subject to exceptions.—*Phil. Mag.*, March, 1878, p. 161.

A. S.

13. *On a method of measuring the Velocity of Light*; by ALBERT A. MICHELSON, Ensign U. S. Navy, Instructor in Physics and Chemistry, U. S. Naval Academy. (From a letter to the Editors.)—The following method of measuring the velocity of light dispenses with Foucault's concave reflector, and permits the use of any distance. In the figure, S is a division of a scale ruled on glass; M, a revolving plane mirror; L, an achromatic lens; S', a fixed plane mirror, at any distance from L.

The point S is so situated that its image S' reflected in the mirror M, is in one focus of the lens L, while the image of S' coincides with the mirror S', which is placed at the conjugate focus. With this arrangement, when M turns slowly, the light from S' is reflected back through the lens, so that an image is formed which coincides with S. When, however, the mirror rotates rapidly, the position of M will have changed while the light travels from M to S' and back again, so that the image is displaced in the direction of rotation of the mirror.

Let V be the velocity of light; D, twice the distance M S'; n, the number of turns per second; *d*, the distance M S and *s* the deflection; then V is found by the formula $V = \frac{4\pi^2 n D^2}{s}$.

In a preliminary experiment the deflection amounted to five millimeters when the mirror revolved 128 times per second.

A. M.

II. GEOLOGY AND MINERALOGY.

1. *On the Limestones of the Falls of the Ohio*, by JAMES HALL. 16 pp. 4to. Advance sheets of vol. v, part ii, of the Palæontology of New York.—Professor Hall reviews the facts with reference to the beds at the Falls of the Ohio and their fossils, gives the results of personal observations, and arrives at the conclusion that the rocks include—beginning below:

(1.) Niagara beds, of the *Upper Silurian*, which are the "Cincinnati beds" of S. S. Lyon.

(2.) Upper Helderberg beds, to which belong the next following strata, (a) Coral beds, (b) Turbo bed, (c) Pentamerus bed, and (d) Spirifer bed, of Lyon.

(3.) Then 20 feet of Hamilton beds, which are of impure magnesian limestone, and comprise (e) the Hydraulic limestone, and (f) the Encrinital limestone, of Lyon.

(4.) The "Black Slate," which, after a special discussion of the facts, is made equivalent to the tiemesse shale of New York.

Professor Hall remarks on the point that the Hamilton period is represented at the Falls only by limestones, mentioning the fact that the formation, which is 1,200 feet thick in the eastern part of New York State, and mainly arenaceous and shaly, with calcareous intercalations among the shales at its base, thins down, to 300 miles westward, to a few hundred feet of calcareous shales with some bands of limestone, and that further west, the limestone gradually becomes still more predominant as the general thickness diminishes; adding that "it is therefore a fair and logical inference that the continuation of this group of strata further west would preserve the calcareous beds alone."

Michelson's First Contribution to Science
(Silliman's Journal, May, 1878)

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ALBERT A. MICHELSON
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University of Chicago, Chicago, Ill.*

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76. On the Effect of Small Particles in the Vitreous Humor. Journal of the Optical Society of America, *9*, pp. 197–200; 1924.
77. Effect of the Earth's Rotation on the Velocity of Light (with H. G. Gale). Astrophysical Journal, *61*, pp. 137–139; 1925.
78. Light Waves as Measuring Rods for Sounding the Infinite and the Infinitesimal. University of Chicago Record, *11*, no. 2, pp. 136–153; 1925.
79. Measurement of the Velocity of Light between Mt. Wilson and Mt. San Antonio (with W. Bowie). Astrophysical Journal, *65*, pp. 1–22; 1927. Contributions from Mt. Wilson Observatory, No. 329; 1927.

MINUTES OF THE MEETING

OFFICERS OF THE OPTICAL SOCIETY

President	Irwin G. Priest
Vice-President	Loyd A. Jones
Secretary	Charles C. Bidwell
Treasurer	Adolph Lomb
Editor-in-Chief	Paul D. Foote
Asst. Ed.-in-Chief	F. K. Richtmyer
Past President	W. E. Forsythe

Elected Members of Council

L. R. Ingersoll	A. H. Pfund
P. E. Klopsteg	W. F. Meggers

SPECIAL COMMITTEES FOR THIS MEETING

Bureau of Standards Committee on General Arrangements for the Meeting (Representing the Director of the Bureau): Frederick J. Bates (Chairman); E. C. Crittenden, Geraldine K. Walker, G. H. Vaneman.

Joint Committee of the Bureau of Standards and the Optical Society on the Optical Exhibition: I. C. Gardner (Chairman); Henry D. Hubbard, Raymond Davis, G. H. Vaneman.

Committee on Exhibition of Books on Optics: Frederick E. Brasch, Chief, Smithsonian Division of the Library of Congress, and Secretary of the History of Science Society (Chairman); A. Fanti, Librarian, Bureau of Standards; I. C. Gardner, Bureau of Standards.

Optical Society Committee on Registration, Hotel Headquarters, and Dinner: Frederick J. Bates.

Optical Society Committee on Visit to the Naval Observatory: C. C. Kiess.

MINUTES OF THE EXECUTIVE COUNCIL

Cosmos Club, October 31, and Bureau of Standards, November 1 and November 3, 1928.

The preliminary report of the Secretary indicated status of the Society's membership on November 1st, as follows:

Regular Members	304
Associate Members	139
Honorary Members	6
Corporation Associates	6
Life Members	8
Total	463

(The membership status given in this report is of October 30. Changes in membership (election to regular membership, etc.) were made by the Council after this report was compiled. Members who had submitted resignations and those dropped for non-payment of dues are taken into account in this table.)

Ten resignations by letter were received during the year. Thirteen members were dropped for non-payment of dues and thirty-three new members elected as associates. The names of these new members were read by the Secretary. Action on the resignations was referred by motion to the Secretary and Treasurer who were given power to accept resignations of those whose dues were paid.

The Committee on Time and Place for next annual meeting reported invitations from the University of Pittsburgh, and Pennsylvania State College. An invitation extended informally by F. K. Richtmyer to hold the next meeting at Cornell was favorably received. It was decided by vote of the Council to hold the next annual meeting in October at Cornell University, Ithaca, N. Y., subject, however, to receipt of a formal invitation from Cornell University and confirmation by the Council at the February meeting.

It was moved that future Councils consider Rochester and Pittsburgh for the meetings for 1930 and 1931 respectively.

The following associates were elected to regular membership:

J. W. Beams	A. W. McMahon
F. G. Brickwedde	D. Stockbarger
R. C. Gibbs	Wm. T. Anderson
R. L. Hanson	Burt H. Carroll
E. A. Harrington	W. H. Fulweiler

J. R. Harrison	R. E. Martin
H. J. Howard	A. H. Poetker
H. D. Hubbard	F. G. Slack
E. O. Lawrence	F. E. Swindells
H. W. Russell	T. R. Wilkins
H. F. Stimson	W. F. Little
F. G. Wick (Miss)	F. M. Kannenstine

It was moved that the Jury of Award of the Ives Medal consist of five members to be appointed by the President. The Council recommended the following appointments for this Committee, viz., Henry Crew, (Chairman), H. E. Ives, K. T. Compton, Theodore Lyman, L. T. Troland. This Committee was appointed by the President and confirmed by the Council.

The matter of publication of the proceedings of the Michelson Meeting was discussed. It was voted that the published proceedings should contain abstracts of papers, portrait of Professor Michelson, a bibliography of the published papers of Professor Michelson, a description of the optical exhibition but not details of exhibits.

A Committee on Publication of the Proceedings of the Michelson Meeting was appointed as follows:

C. C. Bidwell	P. D. Foote
H. D. Hubbard	F. K. Richtmyer

I. C. Gardner

The Council voted that the special arrangement with the American Physical Society for reduced rates for the Journal of the Optical Society for members of the Physical Society be terminated with subscriptions ending December 31, 1929 and that the Treasurer and Secretary of the Physical Society be so informed.

A preliminary report of the Treasurer was presented for filing with the Secretary's records.

The meeting adjourned at 10:30 P.M. to meet November 1st, at the Bureau of Standards.

ADJOURNED MEETING—BUREAU OF STANDARDS—4 P.M. NOV. 1, 1928

The meeting was occupied by discussion of the question of the publication and care of the Society's Records and of the matter of annual publication of the Year Book. The Committee on Care and Publication of the Society's Official Records and Reports was unable to make any definite recommendations and the question was discussed at length by

the Council and the Committee sitting together. Although no definite action was taken there seemed to be general agreement that the Secretary, Treasurer and Business Manager of the Journal at the end of the year should submit for early publication in the Journal formal reports covering the preceding calendar year; and that these reports be published in a definite section inserted between the Optical and Instrument Sections; and that a standard caption and style of composition be adopted and adhered to such as *Optical Society of America, Report of the Secretary, or Report of the Treasurer, or Minutes of the Executive Council;* and that all such reports or notices be listed in the table of contents of the particular number in which they appear and also indexed in the volume.

The question of publication *annually* of the year book was discussed at length. The matter of expense and manner of publication was debated and no definite unanimity of opinion arrived at. There was a strong opinion that a biennial publication of this sort would be sufficient. No vote on the matter was taken.

The meeting adjourned at 5:30 P.M.

ADJOURNED MEETING—BUREAU OF STANDARDS—1 P.M. NOV. 3, 1928

By motion of the Council the Secretary was instructed to communicate with the Secretary of the Physical Society with a view to holding the customary joint meeting in New York in February.

A motion was passed that a registration fee of 50¢ be assessed at the annual meetings to defray the special expenses of the local committee.

It was moved that the deficit for expenses incurred by the local committee for the Michelson Meeting be defrayed by the Society. (Note: The local committee reported later that it had balanced its books; and declined to accept any reimbursement from the Society.)

The Editor of the Journal was instructed by vote of the Council to secure for publication in the Journal the paper of Professor Laurens which was presented by invitation at the Michelson Meeting.

It was moved and passed that the President appoint a committee on revision of the Constitution and By-Laws and that the President be a member of that Committee.

The meeting adjourned at 2:15 P.M.

CHARLES C. BIDWELL, *Secretary*

GENERAL ACCOUNT OF THE MEETING

The Michelson Meeting of the Optical Society of America was held November 1, 2, 3, 1928 at the National Bureau of Standards where the

Society and its guests were welcomed on the morning of November 1 by the Secretary of Commerce.

Its character as a celebration, the importance of papers which were presented, the demonstrations of unusual motion pictures, the simultaneous Optical Exhibition, the unprecedented attendance, and the enthusiasm with which this assembly paid its tribute of honor and respect to Professor Michelson all conspired to make it a most unusual meeting.

The notable event which the Society and hundreds of invited guests celebrated was the semi-centennial of the publication of Professor Albert A. Michelson's first contribution to science. This celebration, with Professor Michelson present as the guest of honor, took on quite spontaneously much the character of an informal birthday surprise party,—the fiftieth anniversary of Michelson's birth as a man of science. There was no set program of eulogy nor formal reviews of the work of the honored guest; but the whole assembly took upon itself to pay its spontaneous tribute of honor and respect to intellect and achievement.

The outstanding paper of the meeting was that presented by Professor Michelson himself,—"Results of Repetition of the Michelson-Morley Experiment." In a lecture room which normally seats hardly more than 300, there had gathered to hear him probably about 500 people, while many more who came were unable to get in. Following this paper Professors Swann, Lyman, Richtmyer, and Miller spoke briefly in appreciation of Michelson's work, and in discussion of this paper.

The session at which Prof. Michelson presented his paper was followed by tea and an informal social gathering in the lecture hall.

On the evening of November 2 over two hundred persons attended the dinner in honor of Professor Michelson. They were much interested to hear Professor Michelson himself and his friend Professor C. E. Munroe tell their reminiscences of Michelson's early optical research at the U. S. Naval Academy.

Another notable event of the meeting was the formal presentation of the endowment for the Frederic Ives Medal to the Society by Dr. Herbert E. Ives, who has commissioned the Society to award the medal (usually biennially) "for distinguished work in optics."

The showing of Prof. W. H. Wright's motion pictures of Jupiter and the demonstration of Technicolor motion pictures were received with such acclaim that it was necessary to repeat them twice in order to satisfy the demand to see them. In the three showings they were probably seen by nearly 1000 persons.

On the evening of November 1, about 120 out-of-town visitors to the meeting enjoyed a visit to the Naval Observatory. The demand for admission to this party was a striking illustration of the interest in astronomy. About 500 persons actually requested tickets and it is estimated that about 700 tickets would have been taken had they been available. Since the observatory authorities did not consider it feasible to handle a party greater than 120, the local committee was obliged to limit the party strictly to out-of-town members and guests, and unfortunately not even all of these could be accomodated.

The attendance at the meeting may be analysed and considered in several ways as will be done below. The actual figures as kept at the registration desk will be given; but it must be understood that the total of persons who attended one or more sessions was far in excess of this registration, as many came who did not register. It is estimated that about 1000 persons attended one or more sessions. There is no record of those who may have visited the Optical Exhibition without attending the meeting.

The registration records are of two kinds: (1) advance registration by mail; (2) registration at the desk in person. The essentially interesting features of the attendance are shown in the following tables.

Distribution between Members and Non-members

	Members	Non-Members
(1) Number who registered in advance	89	315
(2) Number who registered in advance and also reported at the registration desk	86	175
(3) Number who registered at desk without registering in advance	38	219
Total book registration (1)+(3)	127	534
		661
Total number who actually reported at registration desk (2)+(3)	124	394
		518

Distribution between Local and Out-of-Town Registration

	Local	Out-of-Town
Total book registration	380	281
Actual report at desk in person	248	270

Distribution of Local Registration between Members and Non-Members

Members	Non-Members
36	344

Distribution of Out-of-Town Registration between Members and Non-Members

Members	Non-Members
91	190

Estimated Attendance at Various Sessions

Thursday, November 1, A.M.	300
Thursday, P.M., total at three showings of motion pictures	1000
Friday, November 2, A.M.	400
Friday, November 2, P.M.	500
(Many were turned away because the room would not hold the crowd.)	
Saturday, November 3, A.M.	300
Saturday, November 3, P.M.	300

CALENDAR OF MEETING

The sessions of the Optical Society occupied three days, November 1 to 3, inclusive. The Optical Exhibition was open from 9:00 A.M. to 5:00 P.M., October 31 to November 3, inclusive.

Visitors were invited to inspect the laboratories of the Bureau of Standards on Wednesday, October 31 and Monday, November 5, as well as during the days of the meeting.

Thursday, November 1

9:00 A.M. Welcome by the Secretary of Commerce.
Business, Reports and Papers on Geometrical Optics, Photometry, Colorimetry, and Technic.

2:30 P.M. Demonstration of Technicolor Motion Pictures.
Motion Pictures of the Planets.

8:00 P.M. Visit to Naval Observatory.

Friday, November 2

9:00 A.M. Papers on Physical Optics.

2:15 P.M. Extra Session (not on program).
Demonstration of Panoramic Motion Picture Photography by System of Prof. Chrétien.
Informal Communication on the Raman Effect by Prof. R. W. Wood.

3:30 P.M. Paper by Prof. Michelson and collaborators on "Results of Repetition of the Michelson-Morley Experiment."

4:00 P.M. Tea.

7:00 P.M. Dinner in Honor of Professor Michelson.

Saturday, November 3

9:00 A.M. Papers on Biological Optics.

2:30 P.M. Address by Dr. Leonard T. Troland on "Optics as Seen by a Psychologist."
Papers on Physiological Optics.

8:15 P.M. Joint Meeting of the Philosophical Society of Washington and the Biological Society of Washington to which members of the Optical Society were invited. Address by Dr. Selig Hecht on "The Nature of the Sensitivity of Animals to Light."

TITLES OF ADDRESSES GIVEN BY INVITATION

A. A. Michelson, Francis Pease, and Fred Pearson: *Results of Repetition of the Michelson-Morley Experiment.*

Paul R. Heyl: *The History and Present Status of the Physicist's Idea of Light.*

C. J. Davisson: *Electrons and Quanta.*

Arthur H. Compton: *X-Rays as a Branch of Optics.*

R. W. Wood: *Recent Experiments on the Raman Effect.* (Informal presentation, illustrated by exhibit of apparatus used by Prof. Wood.)

John W. T. Walsh: *The Reduction of Glare from Automobile Headlights.*

H. Buckley: *The Theory of Interreflection in Light Wells.*

Leonard T. Troland: *Optics as Seen by a Psychologist.*
Henry Laurens: *The Physiological Effects of Radiation.*
John M. Arthur: *Some Effects of Radiant Energy on Plants.*
W. J. Crozier: *The Phototropic Behavior of Animals.*
F. M. Schertz: *Application of Transmittancy Measurements to Biochemistry.*
Selig Hecht: *The Nature of the Sensitivity of Animals to Light.*

(By arrangement with the Philosophical Society of Washington and the Biological Society of Washington, Professor Hecht's paper was presented at a joint meeting of those societies Saturday evening instead of at a regular session of the Optical Society.)

ABSTRACTS OF PAPERS PRESENTED

Committee on Standards of Photographic Intensity

L. A. Jones (*Chairman*); E. C. Crittenden, Raymond Davis, K. S. Gibson, A. C. Hardy, H. E. Ives, C. E. K. Mees, A. G. Worthing.

RESOLUTIONS DEALING WITH THE PHOTOGRAPHIC UNIT OF INTENSITY PRESENTED AT THE INTERNATIONAL CONGRESS OF PHOTOGRAPHY

At a meeting of the Scientific Section of the International Congress of Photography on the morning of Thursday, July 12, the report of the Committee of the Optical Society of America on the photographic standard of intensity was read, and the adoption of the recommendation relating to the standard itself was put as a motion by Dr. Mees and seconded by Dr. Sheppard.

Mr. Guild of the National Physical Laboratory considered that the definition proposed was not satisfactory since the sunlight was not of a sufficiently defined quality. He was not prepared to accept the standardization of it from Abbot's values. In the National Physical Laboratory, also, no difficulty had been met with in the use of ammoniacal solutions which were not found to change in closed cells, and since pyridine was difficult to obtain in a pure and colorless state, he recommended that ammonia be used instead. This point was also brought up by M. Calsavara of France.

Dr. Slater Price, acting as chairman, reviewed the differences between the English and American Committees, which depended on the fact that the Americans accepted one candle power of sunlight as the ideal standard, whereas the English prefer to accept as the photographic candle one candle power of a lamp of 2360°K. transmitted through the stated filter without reference to sunlight at all. Toy stated that the English Committee would accept such a definition. L. P. Clerc, speaking for the French Committee, stated that they had not been able to have any meetings on the subject, since the matter had not been referred to them before the Congress, and he could not therefore make any statement. Speaking for the Germans, who also protested against not having received any prior information, Dr. Lehmann, Dr. Goldberg, and Dr. Eggert were prepared to accept the proposed unit for the sensitometry of negative emulsions but not for the sensitometry of positive emulsions.

After a long discussion, Dr. Mees accepted the proposals of the English Committee and withdrawing his original motion proposed that the photographic unit of intensity should be defined as one visual candle power of a lamp having a temperature of 2360°K. transmitted through the given filter. M. Clerc and Dr. Slater Price pointed out that the composition of the filter was given to milligrams and recommended that in practice the weighing should be required only to centigrams. Mr. T. Smith of the National Physical Laboratory requested that a tolerance of ± 0.05 mm be fixed for the thickness of the liquid in each division of the cell.

The other two recommendations of the Committee were then discussed at some length, but no definite conclusion was reached.

On Friday afternoon the resolution which had been accepted for the standard of light was withdrawn on the motion of Dr. Slater Price, seconded by Dr. Mees. It was then resolved that the following resolution[1] shall be put in force as a decision of the Seventh International Congress of Photography as soon as it has been ratified by the national committees represented at the Congress:

"The photographic unit of intensity for the sensitometry of negative materials shall be defined as the intensity of a source of radiation having a luminous intensity of one international candle and produced by a gray body at a color temperature of 2360°K, together with a selectively absorbing filter made up as follows: Two solutions compounded according to the following formula, the complete filter to consist of a one-cm* layer of each solution contained in a double cell made by using three plates of borosilicate crown glass (refractive index, D line = 1.51), 2.5 mm thick."

Solution A

Copper Sulfate ($CuSO_4 5H_2O$)	3.707	grams**
Mannite ($C_6H_8(OH)_6$)	3.707	grams**
Pyridine (C_5H_5N)	30.0	cc
Water (distilled) to make	1000	cc

Solution B

Cobalt Ammonium Sulfate ($CoSO_4(NH_4)_2SO_4 6H_2O$)	26.827	grams**
Copper sulfate ($CuSO_4 5H_2O$)	27.180	grams**
Sulfuric Acid (Sp. gr. 1.835)	10.0	cc
Water (distilled) to make	1000.	cc

The other resolutions proposed by the American Committee were not passed.

*With a tolerance of ± 0.05 mm.

**For practical purposes a precision of one centigram will probably be sufficient.

[1] The exact wording of the resolution adopted was somewhat different from that here given. The correct form of the resolution is given in the British Journal of Photography, p. 432, July 20, 1928; and will be given in the report of the O. S. A. committee now in press.

I. C. Gardner — Bureau of Standards

A TELESCOPE OBJECTIVE ESPECIALLY FREE FROM SPHERICAL ABERRATION

Specifications for a telescope objective, to be used by Dr. L. B. Tuckerman in his auto collimator forming a part of his extensometer, demand a 50 mm aperture, an equivalent focal length of 250 mm, longitudinal spherical aberration less than 0.05% of focal length, and a design such that it will be feasible to construct several objectives which shall differ in focal length by not more than 0.05%. To meet this last requirement an air space is necessary to permit adjustment of spacing for compensation of unavoidable differences in construction of individual components. The final design consists of two cemented doublets of barium crown and medium flint with the crown component in each case facing the parallel light and spaced 10 mm. Although there are 6 surfaces, only 4 different curvatures are required (an economy in manufacture) and spherical aberration and departure from sine condition are each well within 0.05% of focal length. The design has been executed and found to be satisfactory. Details of the application of algebraic method to design and discussion of tolerances allowable in the construction will be given.

I. C. Gardner — Bureau of Standards

AN OPTICAL DEPTH GAGE

This instrument is analogous to the self-contained coincidence-type military range finder except that the two optical systems united by the coincidence prism are microscopes instead

of telescopes. The magnifying power is approximately 90 diameters and the axes of the two systems are inclined to each other at an angle of 25°. A range finder coincidence-prism provides a circular field divided by a diameter. The images formed by the two microscopes are brought into the two halves of the field respectively, and are so focused that the dividing line and images are without parallax.

When an object is at the intersection of the two optical axes the images formed by the two microscope objectives are in coincidence at the center of the dividing line. Suitable fine adjustments are provided for bringing the two halves of the field into this relative position with precision. If the object is displaced along the line of sight by as little as 3 or 4 microns, it is detected by the lack of coincidence of the two fields. One therefore has an optical depth gage with a working distance between objective and object of approximately 50 mm, and with the probable error of a single observation of a displacement in the line of sight not greater than 3 or 4 microns. By having the instrument suitably mounted with precision ways, such as are used with the comparator or travelling microscope, displacements normal to the line of sight can be measured in the usual manner. The present instrument has been designed to be used for the measurement of internal screw threads and for this purpose it is provided with a special nose piece carrying an objective prism and an opaque illuminator of novel design. It can be used for any purpose where accurate measurements in the direction of the line of sight, as well as normal to it, are desired. As there is no physical contact between the instrument and the surface to which the measurement is to be made, it is particularly applicable to measurements where the pressure due to physical contact of the more usual methods introduces deformation which prevents the attainment of the desired precision.

A. H. Bennett **Bureau of Standards**

AN INTERFERENCE METHOD FOR THE DETERMINATION OF AXIAL AND OBLIQUE ABERRATIONS

A method for the determination of the axial and oblique monochromatic aberrations of an optical system is described. The results are expressed directly in terms of the phase difference of various portions of the emergent wave front on arrival at any point along the axis or chief ray. The best focus is located at the point of minimum phase residuals. The simplicity of the apparatus, especially the use of but one auxiliary reflecting surface, lessens the probability of large instrumental errors. The method has been applied to several astronomical objectives and the results are presented in the form of contours showing phase difference over the wave front.

Bibliography:
Hartmann, ZS. f. Instrumentenkunde, *24*, p. 110; 1904.
Gardner and Bennett, J.O.S.A. & R.S.I., *11*, p. 441; 1925. Twyman, Phil. Mag. (6), *35*, p. 49; 1917.

John W. T. Walsh **National Physical Laboratory, England**

(*By Invitation*)

THE REDUCTION OF GLARE FROM AUTOMOBILE HEADLIGHTS

In this paper an attempt is made to indicate a method for defining the beam characteristics of motor-car headlights so as to obtain the maximum visibility of objects on the off side of an opposing vehicle.

The method is based on the application of work by Holladay on the lowering of the contrast sensitivity of the eye which is caused by the presence of a glaring source of light in the field of view. Certain skeleton conditions are laid down for fulfillment by headlights in order that a certain figure of visibility may be obtained under specified conditions.

In a final section of the paper the proposal is made that vehicles should be provided with projectors giving a colored beam of light in the rearward direction so as to illuminate the off

side of the road behind them for a comparatively short distance. It is pointed out that this would probably be a very great help in securing adequate visibility on the road when vehicles are passing each other, and it is suggested that experiments should be carried out to determine the best conditions for such a system.

H. J. McNicholas — **Bureau of Standards**

APPARATUS FOR THE MEASUREMENT OF THE REFLECTIVE AND TRANSMISSIVE PROPERTIES OF DIFFUSING MEDIA

The equipment is designed for the measurement of the reflective and transmissive properties of diffusing media under definite and controlled conditions of illumination and observation. The intensity and state of polarization of various incident, reflected and transmitted beams of light are measured as functions of their direction and wave-length composition.

Two separate illumination units are provided, one for unidirectional and the other for completely diffused illumination of the sample. The photometric equipment is stationary. To realize the various desired directions of incidence and observation with the unidirectional illumination unit, the sample and source may each be differently orientated with respect to the fixed direction of observation. The source for completely diffused illumination is also constructed so that the sample may be observed in various directions from the normal to its surface.

The equipment is applicable to the study of various problems. Of these may be mentioned (1) the measurement of color and glossiness, (2) the grading of photographic materials, (3) the establishment of standards of reflection and transmission, (4) the covering power and tinting strength of paints and pigments, and (5) the optical properties of turbid media in their relation to the structure of such media.

This paper will appear in full in Bureau of Standards Journal of Research., Nov., 1928.

Herbert E. Ives — **New York City**

A CAMERA FOR MAKING PARALLAX PANORAMAGRAMS

Description of a camera for making transparencies which when viewed through an opaque line grating show stereoscopic relief through a wide range of distances and angles.[1] The essential feature of the camera is a mechanical coupling by means of which the camera lens, the sensitive plate and grating, and the object photographed, are kept in line as the camera moves from one side to the other of the normal from the camera track to the object.

Bibliography (1) Kanolt, U. S. Patent 1,260,682; 1918.

The present paper will appear in full in J.O.S.A. & R.S.I.

Frank Gray and Herbert E. Ives — **Bell Telephone Laboratories, Inc.**

OPTICAL CONDITIONS FOR DIRECT SCANNING IN TELEVISION

A discussion of the conditions for securing the maximum amount of light in a photoelectric cell placed behind a television scanning disc when an image is formed on the disc by a lens. Due to the breaking up of the image into a finite number of elements the amount of light available increases with the physical dimensions of the whole system. Results obtained with a large scanning disc and a lens forming images of sunlit objects are described.

This paper will appear in full in J.O.S.A. & R.S.I.

Arthur C. Hardy — **Mass. Inst. of Technology**

A RECORDING COLOR ANALYZER

A new recording photoelectric spectrophotometer was described at the Schenectady meeting of this Society. The instrument described a year ago included a galvanometer relay, a

commutator, and other pieces of electrical apparatus which gave considerable trouble in operation. These parts have now been eliminated by operating the motor directly from the amplified photoelectric current.

At present, the instrument covers easily the spectral band from 400 to 700 millimicrons. By means of an adjustable slit, the width of the spectral band reaching the photoelectric cell at any time is maintained at 10 millimicrons. Reflecting power or transparency values are determined with a reproducibility better than 0.1%. The time required for a complete spectral analysis of a specimen is approximately 30 seconds. The results are plotted graphically by the instrument on an 8½ by 11 sheet of paper.

By combining a mechanical integrating attachment with this instrument, the three primary excitation values are computed automatically. Thus, this instrument gives the subjective color sensation under any assumed conditions as well as the objective color analysis.

K. S. Gibson **Bureau of Standards**

APPARATUS FOR ACCURATE AND RAPID MEASUREMENT OF SPECTRAL TRANSMISSION AND REFLECTION

Spectrophotometric apparatus is being designed and assembled at the Bureau of Standards which will eliminate many common sources of trouble, uncertainty and error while utilizing the speed and precision possible with the amplified photoelectric current. The essential features are as follows:

(1) Light is spectrally dispersed before being used photometrically. This prevents undue heating of the sample.

(2) A Van Cittert double monochromator produces this dispersion. Its use greatly reduces stray light and has other advantages regarding purity and intensity of spectral image.

(3) Light of any desired wave length enters a white-lined diffusing sphere through one of three small openings spaced 120° apart in the horizontal equatorial plane, and is diffused throughout the sphere.

(4) From the other two openings two beams of light, taken perpendicularly from the opposite interior surface, are led through a Martens photometer to a photoelectric cell. A scheme similar to Hardy's will enable the amplified photoelectric current to set the photometer automatically for equality of intensity.

(5) Midway between two of the openings in the sphere is a fourth opening, against which is placed the sample (properly shielded from direct illumination) whose reflectance is desired. Light reflected from this sample forms one of the two beams above noted.

(6) By rotating the whole sphere 120° about its vertical axis, the sample and sphere wall are interchanged. The reflectance of the sample in absolute value may thus be obtained without reference to any "white standard."

(7) For transmission measurements, by rotating the sphere 120° farther and placing a diffusing white material at the fourth opening, both beams originate from the sphere wall (effectively two sources, each of accurately uniform brightness). The sample is placed between the sphere and photometer and transferred from one beam to the other in the usual procedure.

(8) The light source may be an incandescent lamp, or a mercury or helium lamp or other source of homogeneous light. In the latter case all wave-length or slit-width errors are eliminated at certain wave lengths, and this advantage is available for reflection as well as transmission measurements

(9) The transmission samples and sphere and (separately) the monochromator are enclosed and the enclosed air may be kept at any desired temperature.

Bibliography:

Van Cittert, Revue d'Optique, *2*, p. 57; 1923.

Hardy & Cunningham, J.O.S.A. & R.S.I., *16*, p. 119; 1928.

McNicholas, B. S. Jour. Res., *1*, p. 29; July, 1928.

O. S. A. Com. on Spectrophotometry, J.O.S.A. & R.S.I., *10*, p. 109; 1925.

H. P. Gage — Corning Glass Works

SPECTROSCOPIC AND COLOR ANALYSIS OF RAILWAY SIGNAL GLASS STANDARDS

In 1908 the Railway Signal Association, now the American Railway Association Signal Section, adopted certain colored glasses as suitable medium standards for railway signals. In order to limit variation due to manufacturing conditions, it was specified that all railway colored glass should be tested against these standards by direct photometric comparison. The original 100 per cent standards were for red, yellow, green, lunar white, blue and purple. With these standards it is possible to accurately assign photometric values to signal glass of approximately the hue of the standards.

In practice a modified Lummer-Brodhun photometer is used employing a mirror with a design consisting of wide and narrow scratches.[1,2] When a hue difference exists the fine scratches can be made to disappear even when the larger areas do not. Consistent photometric settings can be made by the same observer even with considerable hue difference such as between Carbon and Mazda C or Mazda and daylight. Routine inspection has been greatly facilitated by the design of a binocular instrument.[3]

Medium colors adopted in 1918 are defined by a spectrophotometric table.[3,4]

Railway limits defined photometrically have not yet been defined colorimetrically and data will be presented on some preliminary calculations made in accordance with the Colorimetry Report.[5,6] The calculated results are expressed as per cent red, green and violet sensations. Conversion of these factors into dominant hue and purity involves reference to a graph and is therefore liable to error. In the few instances where direct colorimetric observations are made in terms of hue and purity, it is recommended that these be translated into terms of the elementary sensations. The liability to error would probably be less reading the graph in this direction than the opposite.

Bibliography:
[1] Phys. Rev., *32*, p. 628; June, 1911.
[2] Trans. I. E. S., *19*, p. 508; July, 1924.
[3] R.S.A. Specification 6918.
[4] A.R.A., Signal Section Specification 5927.
[5] J.O.S.A. & R.S.I., *6*, p. 527; August, 1922.
[6] International Illumination Congress 1928, paper 7–3.

A. H. Pfund — Johns Hopkins University

A NEW PHOTOMETER-HEAD

In the following it is shown how an essentially perfect photometer-head may be made from ordinary plate or window glass. A crack is first started whereupon the plate is heated locally with a bunsen burner until the crack runs the entire length of the plate. Over a limited region the newly-formed surfaces meet the original ones perpendicularly at all edges. By using such a plate as a photometer-head the line of demarcation can be made to disappear completely. This device, which may be used as an equality or contrast photometer, can be readily transformed into a flicker-photometer.

A. E. O. Munsell and I. H. Godlove — Munsell Color Company, Inc.

WHITE GLASS PHOTOMETRIC STANDARDS

Samples of white glass—where the original smooth glossy surface is not destroyed—offer the most permanent standards for photometric use. Such standards can be obtained in relatively non-selective form. The present work outlines a direct method for determining the spectral curve for such a white glass standard in *absolute terms* together with the integral reflection factor for this standard.

Although a layer of magnesium oxide is assumed to be non-selective, the neutrality of magnesium oxide layers of different thicknesses was determined, through three chromatic filters, on the Pfund multiple reflection colorimeter.[1] Two thicknesses were found balanced about and very close to the neutral point. Spectral curves were obtained, representing the ratio, wave length by wave length, of the magnesium oxide layers to a certain selected white glass standard. An average of these two spectral ratios—weighted in proportion to the relative non-selectivity of the two magnesium oxide samples, which they represented—was obtained, and the reciprocals of this average determined. The resultant spectral curve gave a faithful picture of the non-selectivity of the white glass standard, but the ordinates were not yet in absolute terms. The integral reflection factors for the two magnesium oxide layers in question were determined on a specially constructed Taylor Photometer and these factors were weighted in proportion to the non-selectivity of the magnesium oxide layers. This weighted reflection factor was multiplied with each of the ordinates of the weighted spectral curve, resulting in a spectral calibration of the white glass standard in absolute terms.

This spectral curve, when multiplied by proper visibility factors and integrated, gave the integral reflection factor of the selected white glass standard, also in fundamental "absolute" units.

[1] Physical and Chemical Examination of Paints, Varnishes, and Colors, by H. A. Gardener, Second Edition, pp. 21–23; 1925.

This paper will appear in full in J.O.S.A. & R.S.I.

Richard Hamer **Guelph, Ontario**

A PRACTICAL LABORATORY MERCURY ARC

The author has devised a new improved portable mercury arc for demonstration and laboratory use, that will facilitate the teaching of spectrum analysis. The apparatus consists of an exhausted pear shaped bulb of pyrex about 3 inches in diameter with two insulated sections below. These are formed by a small glass tube projecting coaxially upwards into a wider tube which is sealed on to the lower part of the pear shaped bulb. Each has its own tungsten electrode. The arc is struck between the mercury in the inner tube and that in the outer on tilting the bulb. A little dimple at the top of the inner tube tends to prevent the arc from travelling around and enables one to focus the small intense arc on the slit of the spectrograph The polarity also is important. A current of about 0.8 amperes regulated by suitable resistances is sufficient.

A small condensing chamber may be sealed on above and this may or may not be connected by a sidearm to one of the two insulated tubes of the lower portion. A short tube projects into the condensing bulb from the main bulb thus forcing the condensed mercury to drain down below and help to keep the relative mercury levels constant. Thus the arc persists and a certain cooling action exists also, which assists this.

The advantage over other types experimented with is that this one is compact, convenient, durable, economical, easy to make and easily started. With the cooling and condensing bulb arrangement in addition it can be depended upon to work for an indefinite time, giving almost a point source. By the addition of various alkaline salts other lines than the mercury ones can be demonstrated readily.

(The above paper was read by title.)

C. G. Abbot **Smithsonian Institution**

RADIOMETRIC STELLAR ENERGY SPECTRA

Fifteen stars and the planet Jupiter were observed with a radiometer in the spectrum of a 60° flint glass prism with 40 centimeter objective, used in conjunction with the 100 inch reflector on Mount Wilson. Though the deflections were small, yet by aid of a special reading

scale very smooth and consistent curves were obtained, and these are illustrated by lantern slides.

This paper will appear in full in Contributions of the Mount Wilson Observatory.

C. C. Kiess — Bureau of Standards

THE WAVE LENGTHS OF THE D LINES OF SODIUM IN ABSORPTION AND EMISSION

The Fabry-Perot interferometer has been used recently, at the Bureau of Standards, to determine the wave lengths of D_1 and D_2 in absorption and emission. The source of white light was a point-o-lite lamp. The absorption tube was of pyrex, about 8 inches long, into which sodium was distilled in vacuo. During the experiments it was heated to various temperatures. The same type of tube equipped with electrodes, when excited by a small transformer, served as a bright source for the D lines in emission. The wave lengths thus obtained are presented in the following table, together with similar data from other sources.

	D_1	D_2
Wave lengths of D lines in absorption	5895.923	5889.950
" " " " " emission (Geissler tube)	.923	.949
" " " " " " (vac. arc 6 cm)[1]	.927	.954
" " " " " air (Fabry-Perot)[2]	.932	.965
" " " " " sun (Rowland corrected to AOBS)[3]	.939	.971

Comparison of the absorption wave lengths with those of the vacuum arc at 6-cm and those found by Fabry and Perot from the flame in air shows a difference which may be accounted for as a pressure shift.

Comparison of the absorption wave lengths with those given in Rowland's Table (corrected to the international scale) shows redward shifts of 0.016A and 0.021A respectively for D_1 and D_2. The calculated Einstein shift for these lines is 0.012A, which leaves a residual shift of 0.004A and 0.009A for D_1 and D_2 to be accounted for by other causes.

Present paper will appear in full in B. S. Jour. Res.

[1] Kiess, Bureau of Standards Jour. of Research, *1*, p. 88; 1928.

[2] Fabry and Perot, Comptes Rendus, *130*, p. 495; 1900.

[3] Burns and Kiess, Publ. Allegheny Observatory, *6*, p. 137; 1927.

C. M. Slack — Westinghouse Lamp Company

(Introduced by H. C. Rentschler)

LENARD RAY TUBE WITH GLASS WINDOW

For the widespread study of the effect of cathode radiation in the fields of chemistry, biology and luminescence a need has been felt for a more convenient and portable means of producing these rays.

It has been found possible to obtain glass windows of a certain shape sufficiently thin to allow electrons to be ejected through them at voltages above 20 K.V.

Windows 2.5 cm in diameter can be constructed .0005 cms thick and still withstand atmospheric pressure. This is accomplished by making an indrawn bubble on the end of a glass tube. This is so sealed to the glass envelope that the atmosphere produces a tension which in direction is the same at every point as that imposed during the formation of the bubble.

The simplicity of construction and the lack of grid structure in this form of window suggests many possibilities for its use. One of the most interesting is that of a cathode ray oscillograph in which the photographic plate could be outside the tube.

Bibliography:

P. Lenard, Ann. d. Phys., *51*, pp. 225–267; 1894.

O. Eisenhut, Heidelb. Diss., 1921.

W. D. Coolidge, Journal Franklin Institute, *202*, pp. 693–736; 1926.

F. L. Mohler and C. Boeckner **Bureau of Standards**

RECOMBINATION OF ATOMIC IONS AND ELECTRONS

A paper by one of the authors describes continuous atomic spectra excited in a thermionic discharge with relatively high current and pressure. The continuous bands extending to the violet from each series limit were ascribed to recombination of ions and electrons. In a continuation of this research an analysis of discharge conditions by means of a probe wire has been made in connection with spectrophotometer measurements of the intensity near the probe. On the recombination theory the intensity at a given frequency interval beyond a series limit will depend on the number of electrons of corresponding kinetic energy and on the probability that an effective collision will take place. The probe measurements show that the electrons have a strictly Maxwellian distribution with an average energy that can be accurately measured. Thus the relative probability of recombination as a function of the velocity can be computed. Results obtained in caesium and helium discharges include other relations between discharge characteristics and intensity.

Bibliography:
F. Mohler, Phys. Rev., *31*, p. 187; 1928.

R. M. Langer **National Research Fellow, Bureau of Standards**
(*Introduced by F. L. Mohler*)

LIGHT SCATTERING IN LIQUIDS

Experiments similar to those recently reported by Raman and Krishnan were carried out with very strong mercury illumination and quartz vessels. Lines not present in the source were detected with an E-2 Hilger quartz spectrograph fine slit with an exposure of ten seconds.

Half hour exposures with benzene showed many lines not reported by Raman and Krishnan. A group of doublets due to 3126 and 3132 is especially interesting.

In $C Cl_4$ the lines reported by Raman and Krishnan—Nature, August 25, 1928—were found as well as several others. The group shown in Fig. 1B of the article just quoted was repeated near 5461, 4047, 4078, 3663–50 and 3126–32 as well as 4358. The same group showed on the short wave length side of these lines. Near 4358 these lines of increased frequency (anti-Stokes lines) were almost one-fifth as intense as their mirror images in 4358.

A group of fairly sharp lines around 4358 (H_2SO_4 scattering) appeared broader around 3125 and 3131 while the same group (including several anti-Stokes components) near 2537 looked like a set of bands with diffuse edges. In methyl alcohol the modified radiation due to 2537 although diffuse could be set on to a tenth of an Angstrom unit. In ethyl alcohol the corresponding lines (slightly displaced to the red) were still sharper. They indicate strong absorption bands at about 3.5μ. Such bands have been found, for example, by Coblentz.

The intensity of the scattering of modified wave length increases very markedly in going from 5461 to 2537. Lines which are barely visible near 4358 are often plain near 3125 and very strong near 2537.

J. W. Beams, L. G. Hoxton, and F. Allison **University of Virginia**

AN INTERFEROMETER IN WHICH THE TWO RAYS ARE ACCURATELY POLARIZED IN PERPENDICULAR PLANES

Several types of interferometers using polarized light have been described and in the half shade interferometer a precision of one twenty-thousandth of a wave length is claimed.[1,2] The precision of this type of instrument depends upon a measure of a change in ellipticity of polarized light rather than the usual shift of fringes. It has not, however, been generally used due probably to its sensitivity to slight temperature variations and the necessity of very fine optical parts. In the instrument, here described, the troubles due to temperature variations

have been practically eliminated while a poor quality of optical parts brings about a sacrifice in precision only.

Parallel, monochromatic light passes through a Nicol prism, then a crystal of Iceland spar or double image prism so oriented with respect to the Nicol that the perpendicularly polarized beams formed are equal in intensity. Each of these beams passes some distance to a mirror and is returned as nearly as possible on its path to the front surface of the double image prism where the two beams recombine to form elliptically polarized light. The smallest change in the ellipticity of this light that can be measured determines the sensitivity of the instrument.

This change in ellipticity of the light was measured by placing a half silvered mirror between the source and Nicol and focusing the light and dark bands formed on a system of slits identical in dimension with the bands. The image of these slits falls upon a photoelectric cell and any shift of the bands is recorded by a current through the photoelectric cell. The slit system and photoelectric cell method of measuring fringe displacements is of course not confined to this particular instrument but may be used in any interferometer where reasonably sharp fringes can be obtained.

The sensitivity here attained, although considerably less than that of the half shade interferometer, is larger than that of the ordinary instrument. The factors which limit it are discussed.

[1] Cotton, Comptes Rendus, *152*, pp. 131–133; 1911.
[2] Skinner and Tuckerman, Phys. Zeit., *12*, p. 620; 1911.

C. Boeckner **Johns Hopkins University**

(Introduced by A. H. Pfund)

THE OPTICAL CONSTANTS OF QUARTZ FOR WAVE LENGTHS IN ITS 9μ REGION OF ANOMALOUS DISPERSION

The reflecting power of polarized light from quartz in the 9μ region is obtained at two angles of incidence. From these, by use of the exact Fresnel reflection power formula, the extinction coefficient and index of refraction are calculated for a series of wave lengths. The constants for amorphous quartz and for the ordinary ray of crystalline quartz are obtained.

The exact form of Fresnel's reflecting power formula is verified.

F. M. Schertz **Bureau of Chemistry and Soils, Department of Agriculture**

(By invitation)

APPLICATION OF TRANSMITTANCY MEASUREMENTS TO BIOCHEMISTRY

A brief introductory historical review is given of transmittancy measurements. Spectrophotometric methods of determining the purity of organic compounds are compared with chemical methods now used. Colorimetric and spectrophotometric methods of comparing the concentration of a given substance in solution are compared. Examples will be given showing the application of transmission data to modern biological problems. The principles and procedures of Willstätter when used in connection with spectrophotometric methods offers hope of solving many of the present problems in biology which are not being solved by any present day methods. Details will be given as to how the method can be applied in preparing and testing chlorophyll *a* and chlorophyll *b* so that we may know these compounds are actually the same as those found in all green plants. Our knowledge on chlorophyll can only be extended by being positive that the pigments we are working with possess in every respect the same chemical and physical characteristics, and especially those physical characteristics which only transmittancy data will reveal, as does chlorophyll as it exists in every normal living green leaf. Data on the transmission of organic compounds offers much to the solution of the relation of light to matter.

H. J. McNicholas **Bureau of Standards**

THE ABSORPTIVE PROPERTIES OF CAROTIN AND XANTHOPHYLL IN THE VISIBLE AND ULTRAVIOLET

The absorptive properties of the pure pigments in solution have been measured throughout the visible and ultraviolet spectral range, and the changes in the absorptive properties followed as the pigments slowly oxidized in solution. These data indicate two definite stages in the oxidation of each pigment.

Relations between the frequencies of the absorption bands for each pure unoxidized pigment may be formulated in accordance with the known theory of molecular absorption spectra. The similarity of the absorption spectra of carotin, xanthophyll, chlorophyll-*a* and some derivatives of hemoglobin suggests the presence in each of these pigments of a common nucleus or symmetrical atomic grouping which is the carrier of the observed system of absorption bands.

This paper will appear in full in Bureau of Standards Journal of Research.

Janet Howell Clark **Johns Hopkins University**

MEASUREMENTS OF THE ULTRAVIOLET RADIATION IN SUNLIGHT IN BALTIMORE DURING THE YEAR 1928

A method previously published by the author[1] for measuring ultraviolet radiation, by means of the darkening of a light sensitive paint known as lithopone, has been standardized by substituting C.P. zinc sulphide moistened with saturated lead acetate for the lithopone. The rate of darkening of the zinc sulphide to a standard shade measures the energy of ultraviolet radiation in a band from 350–295 mμ.

Measurements were made every clear day at noon throughout the year and also throughout the day on a number of clear days in every month. These measurements give the daily and yearly variation in solar ultraviolet radiation in Baltimore during 1928.

American Journal of Physiology, *69*, p. 200; 1924.

E. M. Lowry (*Introduced by L. A. Jones*) **Kodak Research Laboratories**

SOME EXPERIMENTS WITH BINOCULAR AND MONOCULAR VISION

An account is given of a series of investigations of the brightness sensibility of the retina, in which both binocular and monocular vision were used. A new type of visual sensitometer is described which enables the operator to determine the brightness functions of the eye in a variety of ways. The instrument consists of a hemispherical bowl, one meter in diameter, equipped with an illuminating system which will give brightnesses from 0.01 to 600 millilamberts. This bowl serves as the sensitizing field. A mechanism is provided by means of which the threshold for brightness may be determined at any adaptation level. Contrast sensibility may also be measured at any brightness as well as the effect on threshold and contrast sensibility of introducing various objects into the visual field. In addition monocular and binocular acuity may be determined using the Ives form of acuity meter. Data and curves are given representing the results secured for a number of observers. Emphasis is laid on the necessity of determining the various functions of the eye binocularly if they are to be correctly interpreted in practice.

This paper will appear in full in J.O.S.A. & R.S.I.

Deane B. Judd **Bureau of Standards**

LEAST RETINAL ILLUMINATION BY SPECTRAL LIGHT REQUIRED TO EVOKE THE "BLUE ARCS OF THE RETINA"

Interest in the "blue arcs of the retina" first described by Purkinje has recently been renewed by Dr. Christine Ladd-Franklin who establishes in a series of communications[1] her

[1] Ladd-Franklin: J.O.S.A. & R.S.I., *12*, p. 494, 1926; *14*, p. 474, 1927; *16*, p. 333, 1928. Comptes Rendus, *185*, p. 584, 1927.

views that the blue arcs are due to the emission of light by the fibers of the optic nerve that pass over the surface of the retina. It has been repeatedly mentioned by Dr. Ladd-Franklin and others (Troland, Amberson, Druault, Ellis) that the blue arcs are obtained more easily with red light than with a stimulus of any other color. This suggests that the origin of the nerve activity causing the blue arcs lies in the retinal cones rather than in the rods, since the rods are relatively insensitive to red light.

The blue-arc phenomenon has been tentatively linked by the author[2] with a certain phase (called the Purkinje phase, or "Bidwell's ghost") of the after-image following momentary stimulation by light of the extra-foveal retina. The Purkinje phase undoubtedly depends on the action of the rods; hence, the two phenomena which are quite similar in some respects would differ in origin if the blue arcs were really initiated by cone action. As a check, then, on the origin of the nerve activity producing them, the blue arcs were aroused by pure spectral light (2° circular field), the retinal illumination being subsequently reduced until the blue arcs no longer appeared. In this way the retinal illumination required to evoke the blue arcs has been determined as a function of wave length for the author's right eye.

It was found that about 0.04 photons sufficed for light of wave length 400 mμ to 530 mμ, whereas about 20 times that retinal illumination, or 0.8 photons, was needed with light of 620 mμ. It may be shown that these illuminations result in nearly equal brilliances by rod vision. Hence, it is concluded that *at the lowest illuminations evoking them*, the blue arcs are due to nerve activity which originates not in the cones, but in the retinal rods.

[2] Judd: Am. J. of Psych., *38*, p. 527; 1927

MOTION PICTURE DEMONSTRATIONS

MOTION PICTURES OF THE PLANETS, MADE BY PROF. W. H. WRIGHT AT LICK OBSERVATORY.

These remarkable motion pictures of Jupiter in rotation which had evoked such applause at the Royal Astronomical Society last summer (H. N. Russell, Scientific American, September, 1928) were shown again by special request at this meeting of the Optical Society. Unfortunately Prof. Wright could not be present to comment on them; but although they are not "talking movies" in the ordinary sense, they did speak for themselves and were highly appreciated.

The following description of these pictures by Prof. Henry Norris Russell in the *Scientific American* for September, 1928 is quoted by permission of the publisher.

We are familiar with the "speeded up" moving pictures which show, for example, the opening of a flower before our eyes, but no one before Professor Wright has had the audacity to think of moving pictures of the rotation of a planet. Jupiter, which completes a rotation in a little less than 10 hours, was chosen for this bold attempt. Only in such a climate as that of California could there be any chance of success, for photographs must be taken at regular intervals of a minute or two all night long—or at least so long as the planet is high enough in the sky to observe satisfactorily. Even so, no single night's work suffices to follow a whole rotation, and two or three successive nights are required before every aspect of the planet has been recorded.

Extraordinary care and eternal vigilance must be exerted to see that the planet's images are all in correct register so that the final image on the screen does not oscillate, but this problem like others has been solved, thanks to the co-operation of Professor Wright and Dr. Mees of the Research Laboratory of the Eastman Kodak Company.

A capacity audience in the historic rooms of the Royal Astronomical Society watched the first showing of the films and broke into the heartiest applause. The diversified surface of the planet was shown in clearest detail and the steady rotation showed itself so simply and naturally that it was hard to realize what pains and labor had gone to speeding it up a thousand times until it became conspicuous to the eye. The Great Red Spot and the smaller details of the surface passed in stately procession across it. At one point in the revolution a satellite appeared at the side of the screen and advanced rapidly toward Jupiter. Just before it reached the planet the shadow of the satellite entered upon the disk, followed a moment later by the satellite itself which in contrast to the black shadow appeared as a pale grayish spot.

These pictures form the most remarkable presentation of the actual progress of stellar motions which has ever been shown. When and how they may become available to a larger public, the writer of these lines does not know. It is greatly to be hoped that they may be widely exhibited and if they are, that all who are interested in the heavens will take the opportunity to see them.

TECHNICOLOR MOTION PICTURES.

Dr. Leonard T. Troland, Director of Research and Process Control, Technicolor Motion Picture Corporation, showed five reels of beautiful pictures in color and supplemented the exhibition with some remarks on the process and the pictures.

(NOTE: Eastman Kodacolor motion pictures were shown as a part of the Eastman Exhibits in the Optical Exhibition.)

PANORAMIC MOTION PICTURE PHOTOGRAPHY BY MEANS OF THE SPECIAL LENS SYSTEM ("HYPERGONAR") OF PROFESSOR HENRI CHRÉTIEN, INSTITUT D'OPTIQUE, PARIS.

Dr. H. Sidney Newcomer presented a motion picture film taken and projected by means of the new cylindrical objective of Professor Chrétien.

The dimensions of a motion picture image as universally used are in the ratio of 3 to 4, in other words the pictures which we are accustomed to see are nearly square. This shape limits the artistic reproduction of many subjects which require additional width or height in order to appear in their entirety in true proportions. To overcome this limitation, in the case of panoramic pictures at least, several pictures have heretofore been projected onto one screen by means of several projectors operating simultaneously. However, in using this method in cinemaphotography, one encounters enormous mechanical and optical difficulties which are practically impossible to overcome. The possibility of obtaining more artistic and complete views of certain scenes where perspective or height is especially necessary to an impressive or realistic presentation of a subject is of great interest to the progressive motion picture art. Professor Chrétien has recently devised a new cylindrical lens combination which offers a very simple solution of this problem.

The special lens enlarges the field of view considerably but in only one direction. The direction of increase of field is chosen according to the demands of the subject. The films presented at the meeting showed pictures which were enlarged horizontally or vertically in the proportion of 2 to 1 according to the orientation of the axial plane of the lens. In this way the angular value of the field of view in one direction is doubled. In other words a view of double the dimensions in either the horizontal or vertical direction is compressed onto a standard size film, and by using the same lens system at the time of projection the compressed image is restored to its normal proportions.

On first thought the lens system seems to recall the anamorphat of Abbe but it differs from this system in two important particulars: (1) The axial planes of the cylindrical lenses which compose the objective all coincide; (2) the image and the object planes of the objective are the same. It is these particular features which place the lens in a category by itself. The second property permits the lens to be used in front of an ordinary photographic objective without disturbing the focus of the latter.

These two special features permit the lens to be easily corrected for astigmatism, coma, and spherical and chromatic aberrations. The distortion is also reduced, but this aberration does not affect the quality of the picture as it is automatically compensated for in the restitution of the image on the screen by projection through a similar optical system.

There are many uses to which this lens can be applied. It is probably sufficient at present to mention two other possibilities. Since the lens compresses the size of images it is possible to print from two negatives of ordinary size placed side by side onto one positive film. When the images are projected and restored to their normal proportions two events which took place at the same time but in different places may be shown simultaneously as if they were projected side by side from two standard projectors operating at once. It is also possible to freely compress a motion picture image so as to leave a considerable lateral free strip of film for the sound record used in the photoelectric production of talking pictures.

THE OPTICAL EXHIBITION

GENERAL ACCOUNT OF THE EXHIBITION

The Optical Exhibition, held in connection with the Michelson Meeting of the Optical Society of America, presented the very newest and some very old exhibits related to the science of optics. These comprised, on the one hand, a display of the new developments of commercial firms and research workers; and, on the other hand, a presentation of books and instruments of historic interest. As a result of the cordial cooperation extended the committee by the exhibitors the purpose of the exhibition was achieved in a gratifying manner.

For a full description of the many individual exhibits reference is made to the catalog of the optical exhibition which forms a part of the supplement to the October, 1928, issue of the Journal of the Optical Society of America and Review of Scientific Instruments.

The eighty-nine commercial exhibits included microscopes, both for research and industrial purposes, color filters, motion picture camera and projection apparatus, color charts, spectrographs, monochromators, photographic objectives, quartz lamps, surveying instruments, colorimetric apparatus, photometers, photoelectric cells, pyrometers, refractometers, turbidimeters, Lenard ray tubes and fused silica ware. Following is a list of the commercial exhibitors:

Bausch & Lomb Optical Company, Brock & Weymouth, Corning Glass Works, Eastman Kodak Company, Gaertner Scientific Corporation, General Electric Company, C. P. Goerz American Optical Company, Hanovia Chemical & Manufacturing Company, Keuffel & Esser Company, Dr. Christine Ladd-Franklin, LaMotte Chemical Products Company, Leeds & Northrup Company, E. Leitz, Inc., Munsell Color Company Inc., New Jersey Zinc Company, Palo Company, The Thermal Syndicate, Ltd., Thwing Instrument Company, Warren P. Valentine, and Westinghouse Lamp Company.

There were current research exhibits by C. G. Abbott, Bell Telephone Laboratories, Inc., Charles Bittinger, L. H. Dawson and E. O. Hulburt, L. E. Dodd and G. H. Jung, Jonas S. Friedenwald, Walter R. Miles, Miss Dorothy Nickerson, the Topographical Survey of Canada, the U. S. Coast and Geodetic Survey, the U. S. Department of Agriculture, and T. R. Wilkins and F. B. Friend.

A group of twelve early microscopes with dates of construction from 1665 to the present, the original Nobert ruling engine, and several

microscope objectives formed an interesting exhibit of great historical value which was loaned from the large collection of microscopes of the U. S. Army Medical Museum. This exhibit was planned and arranged through the courtesy of Major George R. Callender and A. R. French.

The historic development of the science of optics was also illustrated by a most excellent collection of rare books and prints, collected and arranged by F. E. Brasch, Smithsonian Division, Library of Congress, with the assistance of A. Fanti of the Bureau of Standards' library. Important parts of this exhibit were a complete collection of the scientific papers and books of Professor Michelson with a series of his portraits chronologically arranged, the original editions of many early scientific works, a letter in Newton's handwriting, a large collection of current books, and many interesting prints. (The exhibition of books is described more particularly below.)

The exhibits enumerated above were arranged as a formal exhibition in the East building of the Bureau of Standards. The Society appreciated the courtesy of the Electrical Division of the Bureau in lending its rooms for exhibit purposes. These were on the same floor or floors near the assembly room where the meetings were held and proved most conveniently located for visitors to view the exhibits before and after meetings.

Members of the Society and guests visited the different laboratories of the Bureau to see the many interesting pieces of optical apparatus in use and to meet the men who have them in charge. To facilitate this visiting by those in attendance, a list of seventy-nine exhibits was inserted in the catalog listing and describing the apparatus most likely to be of interest and giving full information by which special appointments might be made. The Bureau exhibited the original apparatus used by Rosa and Dorsey for determining the ratio of the electromagnetic to the electrostatic unit which yielded a velocity of light in close agreement with Michelson's latest determination.

The feeling was general that the exhibit was most interesting. An exhibit, in which ingenuity, precision, and scientific design were so much in evidence augurs well for the optical instrument industry and the industries and sciences it serves so well. That two successful systems of color motion pictures were exhibited indicates the more extended use of color in this art. The Westinghouse apparatus for electron discharge through thin glass exhibited a novel new method of research on materials. Colorimetry was well represented as was spectrometry. Raman spectra recently taken were exhibited, evidencing that the new Raman

effect has become one of the new tools of experimental research, extending the means of spectral study far into the infrared. Portable projectors of novel and effective design were shown. Of particular interest to research workers were the many Bureau of Standards exhibits in situ, most of them operating in active research work. It is hoped that this exhibition will point the way to future exhibits of similar scope, for instruments are the logical embodiment of all optical discovery, and will increasingly be the center of interest to workers both in research and applied optics.

EXHIBITION OF BOOKS AND PRINTS

This exhibition was prepared by Frederick E. Brasch, Smithsonian Division, Library of Congress, and Secretary of the History of Science Society, with the cooperation of A. Fanti and Miss Sarah A. Jones of the Bureau of Standards' Library, at the request of the president of the Optical Society. For the courtesy of loans grateful acknowledgment is made to: W. S. Adams, Director, Mt. Wilson Observatory; E. B. Frost, Director, Yerkes Observatory; R. G. Aitken, Associate Director, Lick Observatory; Theodore Lyman, Harvard University; the Carnegie Institution of Washington; the U. S. Naval Academy; the Library of Congress; the Library of the University of Chicago; and James Stokley of Science Service.

The exhibits included:

(1) A collection of rare books, supplemented by portraits of many of the authors, illustrating the historical development of optics from the earliest times.

(2) A collection of modern and current treatises, textbooks and handbooks of optics.

(3) A series of portrait prints of leading American telescope makers and astronomers, and pictures of famous telescopes and other astronomical instruments.

(4) A collection of publications of Prof. Michelson, supplemented by a complete bibliography of his papers prepared for this occasion by Prof. Henry G. Gale of the University of Chicago and Miss Dorothy Bair of the Library of Congress.

(5) A series of seven portraits of Michelson at various ages, beginning with a picture showing him as an ensign at the Naval Academy in 1878 and concluding with one made in 1926.

The following is a catalog of the books of historic interest which were exhibited. Although far from a complete list of books which might

well have been included had they been available, these exhibits were of great interest in showing some of the high lights in the history of optics. The books were arranged chronologically in two large glass cases. The word "portrait" in parentheses indicates that the exhibit was accompanied by a portrait of the author.

ARCHIMEDES, 287–212 B.C. (portrait). *Oeuvres*, 1844. (Reprint.)
CLAUDIUS PTOLEMAEUS, 140 A.D. (portrait). *L'Ottica*, 1885. (Reprint.)
ALHAZEN, 965–1038. (no portrait exists). *Opticae Thesaurus*, 1572.
ROGER BACON, 1214–1294. (portrait). *Opus Majus*, 1928. (Reprint.)
LEONARDO DA VINCI, 1452–1519. (portrait). *Sciences Physico-Mathematiques*, 1901. (Reprint.)
F. MAUROLYCUS, 1494–1575. (portrait). *Cosmographia*, 1543.
G. GALILEI, 1564–1642. (portrait). *Le Opere di Galileo Galilei*, 1892. (Reprint.)
J. KEPLER, 1571–1630. (portrait). *Dioptrics*, 1611. (Reprint.)
R. DESCARTES, 1596–1650. (portrait). *Opera Philosophica*, 1685.
ROBERT BOYLE, 1627–1691. (portrait). *Philosophical Works*, 1725.
CHRISTIAN HUYGENS, 1629–1695. (portrait). *Opuscula Posthuma*, 1728.
ISAAC BARROW, 1630–1677. (portrait). *Mathematical Works*, 1860. (Reprint.)
A. VAN LEEUWENHOEK, 1632–1723. (portrait). *Arcana Naturae*, 1695.
ROBERT HOOKE, 1635–1703. (portrait). *Micrographia*, 1665.
SIR ISAAC NEWTON, 1642–1727. (portrait). *Optics*, 1704.
JAMES BRADLEY, 1693–1762. (portrait). *Miscellaneous Works and Correspondence*, 1832.
PIERRE BOUGUER, 1698–1758. (portrait). *Traité d'Optique sur la Gradation de la Lumière*, 1760.
CLAUDE PASSEMANT, 1702–1769. (portrait). *Telescopia*, 1747.
M. F. LEDERMULLER, 1719–1769. *Nachleese. Seiner mikroskopischen Gemüths- und Augen-Ergossing*, 1762.
J. H. LAMBERT, 1728–1777. (portrait). *Photometrie*, 1892. (Reprint.)
JOSEPH PRIESTLEY, 1733–1804. (portrait). *History and present state of Discoveries relating to Vision, Light, and Colours*, 1772.
SIR WILLIAM HERSCHEL, 1738–1822. (portrait). *Scientific papers*, 1912.
THOMAS YOUNG, 1773–1829. (portrait). *Course of Lectures on Natural Philosophy and the Mechanical Arts*, 1845.
SIR DAVID BREWSTER, 1781–1868. (portrait). *The Stereoscope*, 1856.
J. FRAUNHOFER, 1787–1826. (portrait). *Neue Modifikation des Lichtes*, 1814–1915.
JOHN FARRAR, 1779–1853. (portrait). *Optics*, 1826.
ROBERT W. von BUNSEN, 1811–1899. (portrait). *Gesammelte Abhandlungen*, 1904.
HEINRICH SCHELLEN, 1818–1884. (portrait). *Spectrum Analysis*, 1872.
H. L. F. von HELMHOLTZ, 1821–1894. (portrait). *Ueber das Sehen des Menschen, 1855; Vorlesungen, über die elektromagnetische Theorie des Lichts*, 1897; *Optique physiologique*, 1867; *Handbuch der Physiologischen Optik*, 1867.
GUSTAV R. KIRCHHOFF, 1824–1887. (portrait). *Researches on the Solar Spectrum*, 1862. (Trans.)
G. P. BOND, 1825–1865. *On the relative Brightness of the Sun and the Moon*, 1861.
SIR NORMAN LOCKYER, 1836–1920. (portrait). *Solar Physics*, 1874.
HENRY A. ROWLAND, 1848–1901. (portrait). *Miscellaneous Publications on Wave Lengths of the Lines in Solar Spectrum.*
EDWARD E. BARNARD, 1857–1923. (portrait). *A Photographic Atlas of Selected Regions of the Milky Way.* Pt. 1, *Photographs and Descriptions;* Pt. 2, *Charts and Tables*, 1927.

Another exhibit of particular interest to the history of optics in America was a photostat copy of the manuscript of the first lectures on optics given in America. These were the lectures by John Winthrop, Hollis Professor of Mathematics and Natural Philosophy at Harvard College from 1738 to 1779. This exhibit was accompanied by a portrait of Winthrop and prints showing the brass quadrant, transit instrument and a small reflecting telescope used by him.

A portion of a Newton manuscript, kindly loaned by Mr. James Stokley, was also exhibited.

The exhibit of modern and current texts proved to be a feature of very practical interest to the visitors. It was noticed that many stopped to make note of the titles.

The pictures of telescope makers, astronomers, and famous astronomical instruments included: Rittenhouse, Clark, Brashear, Warner and Swasey, the Lick 36-inch refractor, the Yerkes 40-inch refractor, Hale with coelostatspectrograph at the National Academy, Hale's spectroheliograph, and E. C. Pickering with his photometer with which he made over a million photometric observations on stars.

The collection of portraits and publications of Michelson was of particular interest at this meeting, named in celebration of the semicentennial of his first publication and in appreciation of the results of his half century of research in optics.*

The Optical Society is much indebted to Mr. Brasch for the enthusiasm with which he undertook this task and the labor which he expended in carrying it to a successful conclusion.

This success and the favor with which the exhibit was received suggest that such historical exhibits might well be a feature of many scientific meetings. With experience, encouraged by a growing interest in the subject, these exhibitions would doubtless be improved year by year. Such exhibits, effecting a closer liaison between the History of Science Society and various specialized scientific and technical organizations, would doubtless do much to diffuse knowledge of the history of various subjects and contribute greatly to the advancement of scholarship in all departments of science.

* The bibliography prepared by Prof. H. G. Gale of the University of Chicago and Miss Dorothy Bair of the Smithsonian Division of the Library of Congress is published in full elsewhere in these Proceedings. (Pages 151–154.)

SOME PAPERS PRESENTED AT THE MEETING BY INVITATION

REPETITION OF THE MICHELSON-MORLEY EXPERIMENT

By A. A. Michelson, F. G. Pease, and F. Pearson

This investigation was undertaken with the view of making a more accurate test than had hitherto been obtained and may be divided into three parts as follows:

The first preliminary observations were begun in June, 1926. The principle employed was not essentially different from that in the original Michelson-Morley experiment, with the exception that in this investigation the observer was mounted on the apparatus, revolving with it while making observations.

Several hundred observations were made, all indicating the same negative result as was obtained in the original investigation. According to calculations furnished by Dr. Stromberg a displacement of 0.017 of the distance between fringes should have been observed at the proper sideral time. No displacement of this order was observed.

The second preliminary investigation was begun in the fall of 1927. In this the optical parts were supported on a heavy disk of cast iron, floating on a circular mercury trough as in the original experiments. The chief modification, however, consisted in the fact that the light source was placed vertically over the center of the revolving disk and rotated with it. The return image, by a simple system of reflections, was rendered stationary, thus avoiding the necessity of mounting the observer on the apparatus. The stationary interferometer fringes could therefore be measured in the usual way by means of a micrometer eyepiece, the observer being at rest above the center of the rotating disk. The length of the light path in this experiment was fifty-three feet.

In consequence of inadequate temperature control (and probably unsymmetrical strains in the apparatus) the results, while not so consistent as could be desired, still showed clearly that no displacement of the order anticipated was obtained.

In the final series of experiments, the apparatus was transferred to a well-sheltered basement room of the Mount Wilson Laboratory. The length of the light path was increased to eighty-five feet, and the results showed that the precautions taken to eliminate temperature and pressure disturbances were effective.

The results gave no displacement as great as one-fiftieth of that to be expected on the supposition of an effect due to a motion of the solar system of three hundred kilometers per second.

These results are differences between the displacements observed at maximum and minimum at sideral times. These directions correspond to Dr. Strömberg's calculations of the supposed velocity of the solar system.

UNIVERSITY OF CHICAGO AND MOUNT WILSON OBSERVATORY

THE HISTORY AND PRESENT STATUS OF THE PHYSICIST'S CONCEPT OF LIGHT*

By Paul R. Heyl

There is something peculiar about light. No other physical phenomenon can match it in the intimacy of its relation to the life of man and the esteem in which he regards it. Sound is necessary and desirable at times, but for the most part our estimate of it is expressed by the saying: "Silence is golden." Of heat we seem usually to have either too much or too little, as the case may be. Electricity is a comparatively new acquaintance and dangerous withal. But no one fears the light save the sons of darkness whose deeds are evil. Light is an old friend of the human race, familiar yet mysterious, greeting us daily, yet never wearing out its welcome. Light we must have, natural or artificial, throughout our waking hours, and many an anxious soul has felt the force of the phrase of the Psalmist: "More than they that watch for the morning."

Familiar, yet mysterious; though for thousands of years we have wondered and guessed about it we have to-day no clear and satisfactory mental picture of it such as we have of sound. But if we cannot as yet give a final answer to the question: "What is light?" we may perhaps pass a little time pleasantly and profitably in reviewing what our predecessors thought of it.

It is probable that in the beginning man regarded light as an entity apart from the sun. This idea is found among certain primitive tribes at the present day. It was undoubtedly the concept of the Babylonian intellectuals, for it has come down to us in the creation story in the book of Genesis. The artist Doré has unconsciously given us a good idea of this concept of light. It is a characteristic feature of his pictures that they are often suffused with a soft, uniformly distributed glow of light with no apparent source, suggesting a luminous fog. It is likely that with this ancient concept there went very vague ideas or none at all regarding the nature of this luminous entity, but if we can trust the analogy of all scientific thought prior to the nineteenth century, primitive man doubtless regarded light as of a material nature, much as the clouds that come and go, or the wind that rises and dies away.

* Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

Certain it is that the first recorded concept of light is materialistic. The Pythagorean school of philosophers in the fifth century B. C. held that the sensation of light was caused by the bombardment of the eye by particles emitted by the luminous body. A century later the Platonians altered this concept by reversing the direction of motion of the particles. They said that the eye itself emitted a "divine fire," a stream of particles that reached the body seen, united there with the sun's rays, returned to the eye, and there excited vision.

But from this belief one of the disciples of Plato dissented. The great Aristotle held a theory of the nature of light which, if transliterated into its etymological English equivalent, sounds quite modern. He held that light was energy (*ἐνέργεια*) of a diaphanous (*διαφανές*) medium filling all space; but being in a minority of one among his fellow Platonians, this view did not prevail, despite the authority with which his utterances on other subjects came to be regarded.

Nor did it deserve to prevail, for closely as it appears to simulate modern ideas this was purely accidental. It was as much of a guess and as little based on experiment as were the opinions of his fellow philosophers, and deserves no more consideration.

In using the term *ἐνέργεια* Aristotle of course had not in mind the modern limited scientific signification of the word energy. The Greek word used by him carried the sense of activity or operation as distinguished from habit, and his belief in a medium filling all space was based upon the idea which he held that a vacuum was a philosophical impossibility.

The corpuscular theory of light, it may be seen, is of a respectable antiquity; and though some difference of opinion existed in early times as to the vector direction of the process, the Platonian doctrine that something proceeded from the eye, later to return to it, had sufficient vitality to establish itself and to hold the field for some fifteen centuries.

But perhaps this was not so remarkable as it might seem under present day conditions, for during the first ten or twelve centuries of the Christian era those who paid any attention to scientific theories were as scarce as the proverbial hens' teeth. Learning of any kind was at a low ebb in Europe from the fall of Rome until the invention of printing; but during this period the torch of science was kept alight by the Arabs. One of these Moslem scholars, Alhazen by name, who lived in the eleventh century, returned to the original Pythagorean doctrine that light consisted wholly of particles proceeding from a body to the eye. Alhazen was an astronomer and mathematician of repute,

and because of his authority the corpuscular theory of light returned to its original form, in which Newton found it six centuries later.

The first challenge to this ancient and honorable doctrine came from Huygens, who in 1690 proposed the wave theory of light. Aristotle as we have seen, was rather vague in his description of light as *ἐνέργεια* but Huygens definitely specified the kind of activity which he supposed to constitute light. Huygens' theory received careful attention and study from Newton, who recognized its strong points, and was for a time inclined to adopt it. The "Queries" in his "Opticks" are full of references to supposed vibrations in a medium filling all space, and there is extant a letter from Newton to Hooke in which he says: "Were I to propound an hypothesis it should be this, that light is something capable of exciting vibrations in the ether." But his final judgment led him to the corpuscular theory, largely because of the failure of the wave theory as developed by Huygens to account for the rectilinear propagation and polarization of light. And so for a hundred years more the undulatory hypothesis was put on the shelf, and the corpuscular theory ruled supreme.

The situation as between the corpuscular and wave theories of light which prevailed in the eighteenth century was one which has more than once arisen in physical science. To each theory there were objections to be made, and there was not then available any experimental ground for a final decision between them. That theory which seemed to be open to the last objection was adopted for the time being.

With the opening of the nineteenth century the long reign of the corpuscular theory was brought to an end. The work of Young and Fresnel, especially with regard to the new phenomenon of interference, weighed heavily in favor of the wave theory. The mathematical genius of Fresnel extended the undulatory theory as developed by Huygens to account for the phenomena of diffraction and of rectilinear propagation, thus removing the chief objection that had been raised by Newton against Huygens' theory.

But the wave theory of light did not spring into being like Athena, fully armed from the head of Zeus. Its growth was gradual. Young was at first inclined to regard light waves as longitudinal vibrations after the analogy of sound. It was left to Fresnel, some years later, to show by his experimental and mathematical researches on the phenomenon of polarization, that the vibrations constituting light must be regarded as transverse. The undulatory theory was now com-

plete as far as the description of the mode of vibration was concerned. The next important question was, what was it that was vibrating?

The successors of Fresnel, especially Green and Stokes, suggested that the ether was to be regarded as an elastic solid, something like a tenuous jelly. This theory received the enthusiastic support of Kelvin, and was the orthodox concept until the advent of Maxwell with his electromagnetic theory of light.

Maxwell's contribution to the theory of light was not so much an attempt at an explanation of its nature as it was a correlation—of light with electricity, a reduction of two puzzles to one. Both light and electricity he regarded as phenomena of the ether, but he made no attempt to explain the nature of the ether itself. Rather was the tendency the other way, to explain electricity as state of strain in the ether. Nevertheless this correlation was a step ance, and was but one of a number of such correlations which c erized the physical thought of the nineteenth century. With t advent of Maxwell's theory light lost its individuality, and has s ce been regarded as a department of electricity.

Maxwell's doctrine was generally well receiv ed, and in a short time attained the rank of a classic. It played a large part in bringing about that closely knit structure of physical theory which was the admiration of the physicists of the closing years of the last century. It was recognized, of course, that perfection had not yet been attained. Kelvin remarked in an address delivered in 1900 that there were two clouds in the sky; but there was a general feeling that what had been established was at least approximately correct, and with perhaps a little patching would stand forever.

The suggestion is irresistible that in speaking of these two clouds Kelvin might have prophetically sensed the possibility of their increasing as did those seen by the servant of Elijah. As a matter of fact, this is just about what happened, for one of these clouds was the negative result of the famous Michelson-Morley experiment on ether-drift, which gave rise eventually to the theory of relativity, and the other was a certain imperfection in the theory of the statistical distribution of energy, suggestive of that similar difficulty in the distribution of energy in the spectrum which later led to the quantum theory.

It must be admitted that in spite of the mass of new material which the twentieth century has placed at our disposal the sky is not yet clear; perhaps not so clear as it seemed to be thirty years ago. We of today are possibly no nearer an understanding of the nature of light

than were our predecessors of a generation before. But I think we are better aware of our shortcomings, and perhaps less inclined to over-confidence in our theories. We certainly see more clearly revealed the magnitude of the task before us, and we have girded our loins for a long journey.

The first suspicion that all was not well with the wave theory of light came with the discovery of the x-rays. The nature of these rays was for some time a puzzle. It is true that Röntgen in his first publication referred to them as "a new kind of light," but he was speaking in general terms and perforce used familiar words to describe the unknown. It was uncertain for a time whether the x-rays were akin to light waves at all. Attempts to produce the ordinary optical phenomena with them were disappointing. In particular, no success resulted from attempts at diffraction with the finest gratings that could be ruled. Physicists had already begun to ask themselves whether it would not be necessary to return at least in part to the corpuscular theory of light when it was found that by using the superfine gratings provided by Nature in the structure of a crystal, the x-rays could be made to show diffraction patterns. The x-rays were thus shown to be the same in kind as light waves, though greatly different in degree.

The wave theory, thus relieved of a critical situation, was felt to be all the stronger for the greater breadth and inclusiveness that it had developed; but soon another and more serious challenge arose in the shape of the quantum theory.

The undulatory theory had always tacitly assumed light energy to be continuous in its nature. Our mental picture, as far as we had one, was of trains of waves of indefinite extent, longer or shorter as the case might be, but when emanating from a continuously oscillating source, to all intents and purposes endless. The quantum theory introduced a fundamental change into this concept. Energy, according to Planck, is atomic, existing in finite bundles, discrete units of definite magnitude. This, in effect, was a revival of the corpuscular theory with this important difference: that where the corpuscular theory considered particles of matter the quantum theory postulated atoms of energy, otherwise called quanta.

Just what might be the nature of a quantum was not and is not yet clear. The element of discontinuity, of atomicity which it involves is fundamental, and in so far it may be regarded as corpuscular; but along with this there is associated an element of periodicity rendered necessary by the phenomena of interference. In these two elements

the present concept of the quantum bears a curious resemblance to Newton's moving corpuscles, subject to "fits" of a periodic nature.

Speculation as to the nature of a quantum has not been lacking. One of the earliest suggestions was that it consisted of a train of ether waves, limited in length, which might be called a dart. Since interference can be obtained with difference of path of a few dozen centimeters it was recognized that a quantum must be at least that long. Carrying this line of argument farther, it was pointed out by Lorentz that since interference is obtainable between two parallel rays of light as much as five meters apart (as in the measurement of star diameters) a quantum must be at least sometimes that wide. The simile of the dart was thus replaced by that of a piece of corrugated iron roofing. But a quantum must enter the pupil of the eye in order to excite vision, and with such dimensions as above indicated this operation suggests the celebrated packing of the genie into a bottle.

A few years ago J. J. Thomson suggested that a quantum might be something like a ring or re-entrant Faraday tube of force in the ether, surrounded and enveloped by a system of Maxwellian waves. The interest of this suggestion lies in its illustration of the importance attached today to both the undulatory and the neo-corpuscular concepts. For the satisfactory understanding of some phenomena the spreading wave hypothesis is most suitable; for the explanation of others the non-spreading, corpuscular quantum is best fitted.

In the early days of the nineteenth century it was the undulatory theory which benefited by experimental discoveries. The quantum theory, in its turn, is being fortified by the new discoveries of the twentieth century. In particular, evidence is accumulating that wave motion, without losing its periodic characters, may act very much like a particle. This was first noticed in the case of x-rays, in what is known as the Compton effect. It has long been understood that when light of any frequency is reflected or diffracted there is no change in the frequency of the light. Blue light, for instance, remains blue after any number of reflections. But Compton found that in certain cases the frequency of x-rays after rebound from an obstacle was diminished, much as if blue light should become green by reflection. At the same time conditions were observed which can not be accounted for on any spreading wave theory unless we abandon both the conservation of energy and the conversation of momentum. On the contrary, the assumption that the x-rays travel, not by a continuous spreading wave

but in separate bundles or quanta, has been found to be consistent with both accepted principles and the newly observed phenomena.

The question as to there being a similar effect in the case of visible light waves has not escaped attention. There seemed to be ample evidence that by reflection from ordinary materials there is no such change in wave length. Many thousands of measurements have been made of wave lengths, some on light which has come directly from the source, and some of light which has undergone one or more intermediate reflections, and all such measurements have agreed to a high degree of accuracy. Quite lately, however, Raman has announced an effect of this kind when light is scattered by special substances, chiefly organic. The curious thing about this effect is that most of the light retains its frequency after reflection, as past experiment demands, while a small fraction of it changes its wave length. Wood has recently announced that the difference in frequency beteeen the original wave and that which has suffered change in reflection is in each case equal to the frequency of an ultra red absorption line characteristic of the substance.

In cases such as these waves behave like particles. The complementary case, where particles behave like waves, has recently been discovered by Davisson and Germer. These investigators found that a stream of electrons directed against the face of a large single crystal of nickel are scattered in such a way as to suggest that an electron is a little bundle of waves. Regular reflection may occur after laws similar to those that govern the behavior of x-rays under like conditions. If, however, the stream of electrons is directed against a surface of ordinary nickel, made up of many small crystals instead of one large one, no regular scattering is obtained. In this also the behavior of electrons resembles that of x-rays.

The trend of modern physical thought is toward a blending of the two ideas, wave and quantum, though to what end is not yet evident. It is recognized that both the quantum and the wave theories have a valid reason for existence; that each supplements the weak points of the other. As Lodge says, the two concepts, are like a shark and a tiger, each supreme in its own element and helpless in that of the other. The final form of our concept of the nature of radiant energy will probably be one of a broad and general character of which both the quantum theory and the wave theory will be seen to be special cases.

In speculating on the nature of radiant energy we must not neglect the twentieth century doctrine of the equivalence of matter and energy. It is possible that suggestions leading to the solution of the problem of the nature of radiant energy may come from considerations as to the nature of the matter from which it is emitted. In other words, the quantum of energy emitted from a vibrating atom may be merely a chip of the old block. In this connection the latest concept of the atom—that of Schrödinger—is suggestive.

Schrödinger's atom, like that of Bohr, is electrical in its nature, but the electric charge, instead of being localized in revolving electrons, is distributed throughout the whole atomic volume. This charge may at times suffer a periodic fluctuation in intensity, and in consequence, according to classical principles, emit radiation in the form of trains of waves. It also may emit electrons, which may be regarded as little bunches of fluctuating electric charge split off from the main body of the atom. You have all seen tufts of flame rising from a wood fire. Except for the fact that these tufts do not last more than a fraction of a second, they represent fairly well the emission of electrons from the Schrödinger atom.

I have spoken freely about waves, and have even used the term ether. Is there still an ether, or is this too of historic interest only?

Historic interest it has in plenty. It is at least as old as Aristotle, who supposed space to be full of a transparent medium for no better reason than that he could not conceive of a vacuum. In later years the ether has been upheld on the ground that we cannot conceive of action at a distance.

By this term was usually meant gravitation and electric or magnetic attraction. As far as gravitation is concerned, this objection lost its value when Einstein pointed out that there might be no such thing as gravitational force any more than there is a centrifugal force; that both may be considered as manifestations of inertia aided in the case of gravitation by curved space acting much like a mechanical surface of constraint. For this reason it is sometimes said that the theory of relativity has done away with the ether.

I hardly think this a fair statement. The theory of relativity regards phenomena broadly and generally, and bears much the same relation to the minute and meticulous science of optics that thermodynamices dues to the kinetic gas theory. And again, if relativity ignores the ether, does it not introduce what is to all intents and purposes its equivalent?

The ether was supposed to be a medium filling all space that otherwise would be empty. Einstein supposes space itself to be enough of an entity to have a curvature, and to be "empty" only where and when it is flat. But if space can be bent and can straighten out again, why can it not repeat this process with sufficient rapidity to be called a vibration? And what difference does it make whether it is space itself that vibrates, or something that fills space? Back in every one of our heads is the idea that there is something which philosophers call a "thing-in-itself" which is responsible for our sensations of light and electricity; and whether we spell it ETHER or SPACE, what does it matter?

The quantum theory in its corpuscular aspect does indeed suggest the possibility of getting along comfortably in empty space, provided that the quantum can carry with it some kind of periodicity; but on the other hand the Schrödinger atom, from which quanta are emitted, requires a universal medium, the atom itself having no definite bounds, but extending theoretically to infinity, all atoms being organically, if tenuously united.

The concept of the ether has been indeed protean in its nature, all things to all men. Shifting and chameleon-like as it has been, in some form or another it is still with us, and bids fair to remain. Paradoxical as it may sound, the ether is becoming etherealized. In this it is but sharing the gradual but general dematerialization of all of our physical concepts. From the diaphanous medium of Aristotle, which we can liken to nothing more closely than to a gas, through the elastic jelly of the nineteenth century, we have come to the curved space of Einstein and to the universal electric plenum of Schrödinger.

Man's attempts to fathom the mystery of radiation are but a part of the age old struggle of the mind of man with the whole problem of existence. To the philosopher these attempts viewed as a whole, are of the greatest interest. The history of this struggle presents a succession of hypotheses, prized it may be for a time, then abandoned for something new. The non-scientific may scoff at these apparently fruitless attempts, but the philosopher sees below this shifting surface play the steady course of a stream, a constant, unchangeable driving power which has prompted all this effort and which maintains it undiminished in the face of repeated failure—the wonderful human mind.

Man in his highest moments will not rest content in the face of an enigma. He must make an attempt to solve it. Nature wears the face

of a Sphinx; her endless challenge is: "Explain me! Solve my riddle!" And the mind of man is proud, and will tolerate no defiance. The gauntlet is picked up, and the fight is on.

In the contemplation of this struggle the philosopher is at times impressed with the loneliness of man. The child wonders at that which he sees about him and asks questions of his parents, which it is a pleasure to them to answer as far as they are able. But man has no where to turn for such an answer. He must find it for himself or not at all.

However this quest for an answer may be regarded by the scornful, the philosopher sees in it something more than mere curiosity. The phenomenon is too broad and too deep to allow of that explanation. In his own human relations, man recognizes that when his child is old enough to ask an intelligent question he is by the same token old enough to receive at least an elementary answer. Now man alone among animated Nature is endowed with the capability of recognizing the problem of the universe, and of formulating questions about it; and he feels that an answer is no more than his birthright.

Not that Nature withholds this birthright from him. She answers experimental questions, it is true, but her answers, like those of the Delphic oracle, require interpretation, and herein lies man's difficulty. Not as a human parent shapes the answer to the immature intelligence that asks the question does Nature answer man. Rather does she say: "Here is the answer. He that hath ears, let him hear!"

Perhaps we are not yet as far advanced as we think ourselves, and our task for the present is to learn of Nature the rudiments of our mother tongue.

BUREAU OF STANDARDS,
WASHINGTON, D. C.

ELECTRONS AND QUANTA*

By C. J. Davisson

When I discovered on looking over the announcement of this meeting that Prof. Compton is to speak on "X-rays as a Branch of Optics" I realized that I had not made the most of my opportunities. I should have made a similar appeal to the attention of the Society by choosing as my subject, "Electrons as a Branch of Optics." And a very good case can be made out that electrons should be so regarded. During the last few years we have come to recognize that there are circumstances in which it is convenient, if not indeed necessary, to regard electrons as waves rather than as particles, and we are making more and more frequent use of such terms as diffraction, reflection, refraction and dispersion in describing their behavior. If this in itself is not enough to mark electrons as a branch of optics, it is sufficient at least to establish a certain community of ideas between the subjects of optics and electronics which cannot but be of interest to the members of this Society.

The evidence that electrons are waves is similar to the evidence that light and x-rays are waves. A beam of electrons is scattered by a grating—either the lattice grating of a crystal or an ordinary optical grating—and the intensity of scattering, as measured by the current density of electrons proceeding in different directions, is such as can be explained by assuming as is done in optics that what we are dealing with is the superposition of trains of scattered waves proceeding from the grating elements. In other words, current density of scattered electrons displays in these experiments the same type of spacial distribution as flux density in the analogous experiments in optics,and the observations are given a similar interpretation—an interpretation, that is, in terms of the interference of coherent wave-trains. The standard methods of optics are at once available for calculating the wave lengths of electrons of various speeds. We do not hesitate to make these calculations, nor do we hesitate to attach physical significance to the results.

* Paper presented by invitation, at the Michelson Meeting of the Optical Society of America, Washington, November 2, 1928. The title on the advance program was "The Scattering of Electrons by Crystals."

The experiments by which these phenomena are revealed have been made by Dr. Germer and myself in New York, by Thomson and Reid in Scotland, by Rupp in Germany, by Rose in England, by Nishikowa and Kikuchi in Japan and by Sczceniewski in France. The subject is being actively cultivated at present, and there may be still other experiments of which I have not yet heard. I do not propose to give a detailed description of any of the investigations. The type of result and the methods of treating the data are so exactly those of optics—including, of course, x-rays as one of its branches—that the details would hardly interest you. I shall have something to say later on about the general nature of the results, but to begin with I shall attempt a brief account of certain theoretical speculations in which these results were more or less definitely anticipated.

It is a remarkable circumstance, and one that attests to the exceptional insight and daring of Louis de Broglie, that these newly discovered properties of the electron were suspected, and a definite hypothesis concerning them was formulated, two or more years before any of the experiments I have mentioned had been performed; even the exact relation between the speed and wave length of the electron was accurately predicted. It is true that Einstein had at an even earlier date made use of the idea that an assemblage of gas molecules may for certain theoretical purposes be regarded as equivalent to a system of standing waves, but de Broglie seems first to have seen clearly that the duality of wave and corpuscular properties to which we are becoming reconciled in the phenomena of light might be characteristic also of electrons and material particles in general.

If light and x-rays behave in certain circumstances as if they are particles, why should there not be circumstances in which particles behave as waves? This question was suggested to de Broglie not by any idea of the general fitness of things, nor by any sense of symmetry in the universe, but by the realization, which he shared with others, that the laws of classical mechanics had been so amended in the Bohr atom model as to have become all but non-existent. It was generally felt that the Bohr atom had become too artificial to be acceptable, and that the real trouble arose from an unwarranted extrapolation of classical mechanics to systems of atomic size.

To understand the hypothesis on which de Broglie hoped to build a new model of the atom it will be necessary to have clearly in mind the evidence that light is in some sense corpuscular. The idea had its

inception in Einstein's speculations in regard to Planck's theory of the distribution of energy in the spectrum of a black body radiator. It was conceived that the energy radiated by one atom remained in some way localized in space, and could be delivered in toto to another atom or resonator suitably constituted to receive it. From this hypothesis Einstein predicted the relation which was later found to obtain between frequency of radiation and maximum electron energy in photoelectric emission, and the idea has become more and more essential to the understanding of the photoelectric phenomenon as the facts concerning it have been more and more fully revealed to us by experiment. Energy in amounts $h\nu$ is absorbed from radiation of frequency ν not by slow accretion from waves, but instantaneously as from particle impact. The picture seemed clear enough; the energy of a beam of light is carried by corpuscles, each corpuscle transporting the amount $h\nu$. If we were willing, for the sake of pursuing this idea further, to disregard the whole gallery of interference phenomena with which it apparently conflicted, we could show that if the corpuscles possess energy $h\nu$ they must possess also momentum $h\nu/c$—this relation being required to explain the observations on light pressure in terms of impinging particles.

Thus the corpuscular theory seemed to be required to explain the photo-electric phenomena, and it might be made to explain also the phenomenon of radiation pressure. On the other hand the light corpuscle seemed a strange and ephemeral sort of particle, lacking that continuity in time which we attribute to electrons and atoms. Apparently it was manufactured within an atom for the express purpose of carrying away a part of its energy, and was later destroyed in another part of the material universe to which this quantum of energy was delivered. It was difficult to regard an apparently transient entity this sort as a particle in good standing to be classed with electrons and alpha rays.

If a certain suspicion still attaches to the light quantum in respect to its continuity, this suspicion has at any rate been considerably allayed, and the reputation of the quantum as an authentic particle correspondingly enhanced, by the discovery of the Compton effect, and again quite recently by the discovery of the Raman effect. In the first of these phenomena we see the quantum surviving an encounter with an essentially free electron with which it exchanges energy and momentum in accordance with the ordinary laws of elastic collision;

in the latter we see the quantum preserving its identity through an encounter with a molecule to which it imparts a part only of its energy.

If we are required by these recent developments to accept quanta as actual particles which carry the energy and momentum of light, how, in terms of such particles, are we to explain interference?—how are we possibly to get on without waves?—We even depend upon the waves to supply us with information concerning the energy and momentum of the quanta. One way in which it has been proposed to resolve the difficulty is to relegate the waves to the comparatively unimportant role of supplying the laws of motion of the quanta. Let us assume, for example, that when a stream of quanta passes through a narrow slit the particles do not continue in straight lines as Newton supposed, but that they spread out in such a fashion that the current density of quanta proceeding in different directions is proportional to the intensity of the light proceeding in these directions as calculated on the wave theory. In making this assumption we have given over classical mechanics and explained diffraction—or at least described it—by setting up a form of wave mechanics in its place.

With this rather crude and incomplete picture before us of light quanta being guided in their motion by waves, it is not difficult to imagine the general trend of de Broglie's speculations. de Broglie sensed that electrons like quanta might have waves to guide them—to supply the laws of their motion. That the ordinary laws of mechanics are adequate to describe the motions of electrons in discharge tubes is not inconsistent with this view, for it is well known that these laws are adequate also for a corpuscular theory of light to within the accuracy with which the phenomena are described by geometrical optics. It is only when one tries to explain diffraction that the simple corpuscular theory fails him. de Broglie envisaged a similar situation in regard to electrons—a range of small scale phenomena requiring a wave theory for their proper description. Assuming the frequency of these hypothetical waves to be given by the total energy of the electron divided by h, de Broglie was able to show that the length of the waves would be given by h divided by the momentum of the electron—and this, as it happens, is just the relation which obtains between the wavelength and monentum of quanta.

The goal toward which de Broglie was striving, as I have mentioned, was a new theory of the atom, and he was able to point at once to a suggestive relationship which exists between the lengths of these

hypothetical electron waves and the lengths of the circular orbits in the Bohr atom. The permitted orbits are just those which contain an integral number of these electron wave-lengths. But it was Schrödinger, as we all know, who elaborated these ideas into a comprehensive wave theory of mechanics, and showed the tremendous possibilities of this theory in explaining the properties of the atom as revealed to us by the data of spectroscopy. At last we have an atom endowed with a constitution rather than a set of by-laws.

The success of the Schrödinger theory in explaining in a natural way the stationary states of the atom and the various rules governing transitions between these states, not to mention numerous others of its successes, must be taken as very strong evidence in favor of the fundamental idea upon which the theory is based—namely, that the duality of wave and corpuscular properties which characterizes light is characteristic also of electrons. If the evidence supplied by these data lacks something in the matter of directness, this deficiency is made good by the experiments on the scattering of electrons by crystals about which I am supposed to be speaking.

If I have been a long time in coming to the point, the time has not been wasted, for with the picture before us of the energy and momentum of a beam of light being carried by a stream of quanta for which the waves serve only to supply the laws of motion, a workable theory of the scattering of electrons is at once at hand—to a first approximation we merely read "electrons" for "quanta," and there we are. The observations on electron scattering are consistent with the view that the electrons are being guided by waves in just the way we have imagined quanta to be guided in the phenomenon of optical diffraction. The only real difficulty seems to be that in the light phenomena it is not easy to believe in the particles, while in the electron phenomena it is hard to have faith in the waves.

Before going further I should like to point out that we now have two wave lengths associated with an electron of given speed: one is the length of the x-ray waves which will be generated if the whole of the kinetic energy of the electron is converted into radiation and the other is the length of this new de Broglie wave, the so-called phase wave. The first of these wave lengths is inversely proportional to the energy of the electron while the second is inversely proportional to its momentum. In terms of the equivalent voltage V of the kinetic energy of the electron the lengths of the two waves are given in Angstrom units by the formulas

$$\lambda_x = \frac{12350}{V} \text{ and } \lambda_p = \left(\frac{150}{V}\right)^{1/2}$$

and their ratio is given approximately by

$$\frac{\lambda_x}{\lambda_p} = \frac{1000}{V^{1/2}}.$$

For values of V below, say, 10,000 volts the x-ray wave length is much greater than the corresponding de Broglie wave length.

The lengths of de Broglie waves of electrons which have been accelerated through potential differences comparable with 100 volts are the same as the lengths of moderately hard x-rays. For this reason crystal diffraction of de Broglie waves is observed with electrons of relatively low speeds—speeds corresponding to 100 volts or less—whereas, to observe the same phenomenon with x-rays the tube producing the radiation must be operated at potential differences comparable with 10,000 volts.

The first clear evidence of the diffraction of x-rays was obtained when Laue and his collaborators investigated the scattering of x-rays—of x-ray quanta, shall we say—by a single crystal of zincblende. The analysis of this phenomenon led to the prediction and discovery of the Bragg reflection as a special case of crystal diffraction, and later on to the prediction and discovery of the special case of diffraction by aggregates of small crystals of random orientation. All three of these types of diffraction have now been observed with electrons. The Laue type of diffraction and also the Bragg type have been observed and investigated by Dr. Germer and myself. Diffraction by the crystal aggregates has been studied by Thomson and Reid, by Ironside and by Rupp. And observations by the Bragg method have been made also by Szczeniewski and by Rose.

I must now modify to a certain extent the picture of electron diffraction which I suggested to you a while ago. It is not quite true, as I suggested, that the only difference between the diffraction of light waves and the diffraction of electron waves is that in one case the pattern is formed by light quanta and in the other by electrons. In our investigation of the Laue type of diffraction we find, for example, that the streams of electrons which issue from the crystal do not coincide exactly in direction with the streams of quanta which would issue from the same crystal if the experiment were made with x-rays. In the case of

x-ray diffraction the streams of quanta proceed from the crystal in the directions of regular reflection from important sets of atom planes of the crystal, or nearly so. It is recognized that the Laue beams do not, in general, lie precisely in these directions because of a very slight refraction of the rays by the crystal. The situation in regard to electrons seems to be that electrons also are refracted and much more strongly than x-rays. The refractive indices of a metal such as nickel for electrons of low speed depart from unity much more widely than do the indic s for x-rays of equal wave length. It is a consequence of this difference that the departure from the simple law governing the directions of beams, which in the case of x-rays is negligible, is, in experiments with low speed electrons, marked and important.

Fortunately we are not prevented by this complication from arriving at perfectly definite values of wave lengths from observations on the Laue type of electron diffraction, and these wave lengths turn out to be in acceptable agreement with the values of h/mv, as predicted by de Broglie.

Further evidence of electron refraction is contained in the observations we have made on the electron analogue of the Bragg x-ray reflection beam. And from the data of these experiments we have constructed a dispersion curve for nickel which displays some of the features to be expected from certain theoretical considerations. In conjunction with these measurements we have made additional determinations of electron wave lengths, and these agree within one per cent or less with the values calculated from de Broglie's formula.

In the similar experiments made by Szczeniewski and by Rose no certain evidence of electron refraction has been found. This may be due to some important difference in regard to refraction between bismuth and aluminum, the crystals employed in these experiments, and nickel, the crystal upon which our measurements were made. On the other hand Rupp has found evidence of refraction for a number of metals in measurements which he has made on the diffraction of low speed electrons by crystal aggregates.

Electron diffraction differs from x-ray diffraction also in the matter of resolution. The x-ray beams are ordinarily extremely sharp because of the very great number of elements comprised in the diffracting lattice. Much broader beams are met with in electron diffraction—particularly in the diffraction of low speed electrons—and occurrences of the beams are much less critical in wave length. These character-

istics are explained by the slight penetration of the electrons—and therefore of the electron waves—into the crystal; the effective number of scattering centers is small and the resolving power of the grating is correspondingly low.

The diffraction of electrons by crystal aggregates has been studied in Aberdeen by G. P. Thomson, who first observed this phenomenon, and by Rupp in Göttingen. Thomson has worked with thin polycrystalline films of various metals and with high speed electrons for which the refractive indices are practically unity. The results which he has obtained are in perfect agreement with those obtained in the corresponding experiments with x-rays—electrons of a given wave length form exactly the same series of diffraction rings as would be formed by x-rays of the same wave length.

Those of us who are studying electron diffraction are most fortunate in having before us a perfect model for our experiments and a fund of valuable data in the vast amount of work which has been done in the last fifteen years on the diffraction of x-rays. It is for this reason that, in spite of a rather difficult technique, so many and such varied results on electron diffraction have been obtained in less than two years. Already we have passed on from crystal diffraction to diffraction by optical gratings. The first results of this sort were reported a month or so ago by Rupp and are in agreement with our expectations. Electrons are diffracted by an optical grating as if they were waves of length h/mv.

I have still to mention the beautiful but puzzling results which have been obtained in Japan by Nishikawa and Kikuchi. It is too bad to have to conclude my remarks with mention of the only results so far obtained which are distinctly puzzling. Nishikawa and Kikuchi have been studying the scattering of high speed electrons by thin sheets of mica and calcite. The method of their experiment is identical with that of the original Laue experiment except that the heterogeneous beam of x-rays is replaced by a homogeneous beam of electrons. The results, as I have mentioned, are puzzling. If the incident beam is homogeneous, as stated, it is equivalent to a beam of monochromatic waves, and no diffraction pattern—or at most a very simple one—should be observed, and yet when extremely thin sheets of mica are employed elaborate and beautiful patterns of sharply defined spots are obtained—and patterns which cannot be readily explained even on the assumption that the incident beam contains a large range of wave

lengths instead or a single wave length only. When the speed of the incident beam is changed, the form of the pattern remains the same but its scale factor is altered. This also is unlike anything observed with x-rays. The results are such as might be expected if the diffracting system were a two-dimensional mesh rather than a three-dimensional lattice.

When somewhat thicker sheets of mica are used, the pattern of sharply defined spots is replaced by an array of rather fuzzy rings and lines. Again the observations are contrary to our expectations, and their explanation is far from obvious.

It may be significant that these are the only experiments so far reported in which the diffracting material is an insulator.* But whether the clue lies here or elsewhere it is highly unlikely, I think, that the explanation of these results will be found to conflict with the conceptions we now have of electrons which are sometimes particles and sometimes waves.

BELL TELEPHONE LABORATORIES
NEW YORK, N. Y. OCTOBER 30, 1928.

* I was reminded after the meeting by a member of the Society that Thomson and Reid reported experiments on the scattering of electrons by thin films of celluloid—an insulator.

THE REDUCTION OF GLARE FROM AUTOMOBILE HEADLIGHTS

By John W. T. Walsh

INTRODUCTION

The solution of the problem of glare from automobile headlights depends on (i) the production of a beam of standard light distribution and (ii) the specification of the final distribution which combines a good driving light with absence of intolerable glare. The former of these problems has been dealt with by Mr. L. B. W. Jolley[1] and it is the purpose of the present paper to consider the second requirement.

A very large number of anti-dazzle devices are in existence[2] but there has only been one serious attempt to produce a specification for a satisfactory beam distribution. This was first published in 1918 by the American Illuminating Engineering Society[3] and it was based on the assumption of a fixed light. In France, and more recently in other countries, a "dipping" beam is now receiving favor, however, so that both types of headlight must be regarded as possible solutions of the problem.

A good driving light cannot be entirely free from glare so that research is needed to determine what is the beam distribution which will give the best compromise. It may, probably, be assumed that a driver requires a candle-power of at least 6000 from each of his pair of headlights and that this candle-power is needed in all directions between the horizontal and 2° downward, over a total lateral spread of at least 3°.[4] Since it is only the rising light that causes glare to other users of the road, it is only the upper part of the beam which will be considered in what follows.[5] Moreover, apart from glare considerations there is no necessity to limit the candle-power anywhere in the beam and many headlights now in use have a symmetrical distribution with an axial c.p. of 30,000 or more. Such headlights are very valuable to the driver and are quite allowable when the road is

[1] World Power, p. 122, March and p. 197, April, 1927.

[2] Optical Soc., Trans., *23*, pp. 256 et seq., 1921–22; L. B. W. Jolley, *loc. cit.*

[3] Trans., *13*, p. 259; 1918, and *17*, p. 103; 1922 (revised).

[4] This cp gives 0.5 f.c. at 150 ft., the distance covered in 2.5 secs. at a speed of 40 m.p.h.

[5] The glaring effect of reflection in the road surface is here neglected, but it is of great importance when the road is wet or shiny.

clear. There are, then, two distinct conditions to be studied, viz., the "clear road" condition when only the driving light has to be studied, and the "passing" condition when the car considered is meeting another car travelling in the opposite direction. It is clear that when fixed lights are used the same light distribution must serve for both conditions of use. In the case of the dipping light only the distribution in the "dipped" position needs to be considered from the point of view of glare.

CONDITIONS FOR MAXIMUM VISIBILITY

The first problem to be solved is that of determining the visibility which can be obtained with a headlight beam of a given candlepower distribution in the presence of a second similar headlight facing the observer. Alternatively the beam distribution which gives a specified visibility under the same conditions may be determined.

For the purposes of this paper, "visibility" may be defined as the value of the ratio of actual contrast to be perceived to the minimum contrast just perceptible under the specified conditions of field brightness and glare. If the brightness of the object to be noticed is B and that of its background is B', the visibility $V=(B-B')/\delta B$ where $\delta B/B'$ is the minimum perceptible contrast (Fechner's fraction). When B' is zero, δB is the threshold brightness, i.e. the least brightness which will render an object just visible under the prevailing glare conditions.

Researches on glare by Bordoni[6] and Holladay[7] have shown that the glaring effect of a source of small dimensions, such as a motor car headlight, is independent of the size and brightness of the source as separate factors and is governed only by the illumination, E, which the source produces at the observer's eye and on the angular distance D of the source from the object to be discerned.

Holladay found that for values of E lying between 0.25 and 6 m.c., and for angles from 2.5 to 25°, the combined effect of these two factors could be expressed by the statement that the minimum contrast perceptible with a field brightness B with glare present was equal to that with a field brightness $B+9.2\ (E/D^2)$ when there was no glare. In this formula E is measured in foot-candles, D in degrees, and B in candles per square foot. Since δB is known for all values of B when

[6] Comm. Int. de l'Eclairage, 6 me. Session, Genève, Receuil des Travaux, p. 349; 1924.
[7] J.O.S.A. & R.S.I., *14*, p. 1; 1927.

no glare is present, this formula enables V to be calculated under all conditions. Unfortunately the formula is only empirical and was obtained under conditions which did not exactly correspond with those of the headlight problem. It is more than likely, therefore, that further research will result in a modification of these results.[8] It is, in fact, only possible to indicate the method of attack, and any numerical results obtained in this paper must be regarded as provisional and almost certainly subject to modification when more research has been completed.

DEFINITION OF THE CONDITIONS

It is first necessary to make some simplifying assumptions concerning the disposition of the lights with respect to each other and to the driver's eyes. It will be assumed (see Fig. 1.)

(a) that both cars are fitted with lights of identical light distribution;
(b) that all the lights are properly adjusted so that the axis of the beam is horizontal and parallel with the center line of the road in all cases;
(c) that the driver's eye is at a height h feet above the headlight level;
(d) that the cars approach each other in such a way that the distance between the driver's eye and the off-side headlight of the car he meets is constant and equal to d feet, measured perpendicularly to the center of the road;
(e) that the road surface is quite black when seen from behind a headlight with no car coming in the opposite direction;
(f) that it is desired to pick out an object at any distance up to l in front of the car;
(g) that the reflection factor of the object to be discerned is ρ;
(h) that the object to be discerned is situated on the axis of the driver's off-side headlight, as this is probably the worst likely condition from the point of view of glare.

THE CALCULATION OF VISIBILITY

It may probably be assumed that any object between the driver and the opposing car will be visible by silhouette, so that it is sufficient to

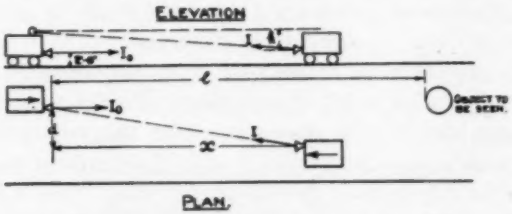

FIG. 1. *Diagram illustrating the assumed conditions.*

consider objects alongside or beyond the opposing car up to a maximum distance l. The brightness of such an object will be $I_0/\pi l^2$ candles

[8] W. S. Stiles, Comm. Int. de l'Eclairage, 7 me. Session, 1928, Receuil des Travaux.

per sq. ft. Although Holladay's work was carried out with field brightnesses of finite, though low, values it is probably not unsafe to assume that the effect of the glaring light, under conditions of perfect blackness of the background is exhibited by the curve in Fig. 2 which gives the value of δB as a function of E/D^2. This curve has been obtained

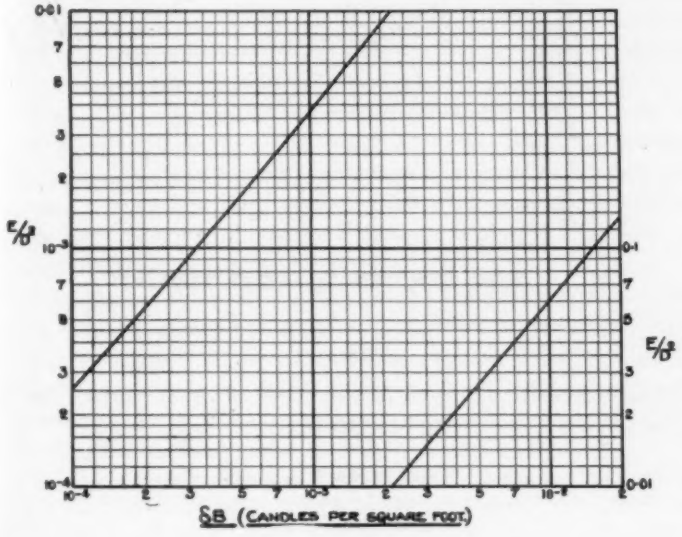

FIG. 2.

from Fig. 3 which gives the values of Fechner's fraction, $\delta B/B$, at all values of B.

Now under the conditions assumed above

$$E = Ix/(h^2+d^2+x^2)^{3/2}$$

where I is the candle-power of the headlight and x the distance between the cars measured parallel to the center-line of the road. Also

$$\cos D = (h^2+lx)/\sqrt{(h^2+l^2)(h^2+d^2+x^2)}$$

so that, since h and d are small compared with x and l,

$$E/D^2 = I/(57.3)^2(d^2+h^2(x-l)^2/l^2)$$

remembering that D is measured in degrees. Thus δB may be found from Fig. 2 and, since B is equal to $\rho I_0/\pi l^2$ and B' is taken as zero, V can be calculated. The following table gives the values of V corresponding to different values of I_0 when I/I_0 has the constant value 0.1 and $h=1.5$, $d=5$, $x=100$ and $l=150$ feet.

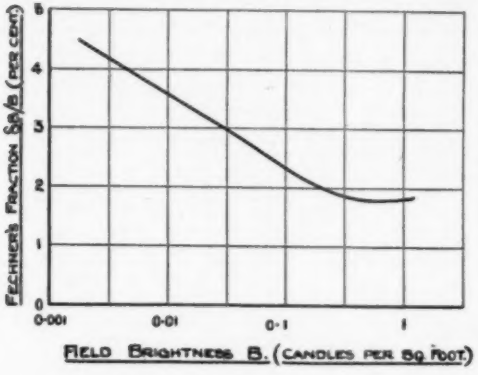

FIG. 3.

TABLE 1. *Visibility when passing.* ($I/I_0=0.1$)

I_0 (candles)	I (candles)	E/D^2	δB (c/sq. ft.)	B (c/sq. ft.)	$V=B/\delta B$
2,000	200	0.0024	0.00071	0.00284	4.0
5,000	500	0.0060	0.00147	0.0071	4.8
10,000	1000	0.012	0.00252	0.0142	5.6
20,000	2000	0.024	0.00485	0.0284	5.9

It will be seen that the effect of increasing the absolute values of both I and I_0 ten times is to increase the visibility by about 50 per cent when two cars are meeting and are still 100 feet apart. Under "clear road" conditions, assuming an arbitrary figure of 0.0001 candle per sq. ft. for the brightness of the background[9] so that $\delta B=0.000015$ c/sq. ft., $V=0.095\ I_0$ numerically. Thus, for both conditions, increase in I_0 leads to an increase in V, though naturally to a much less extent in the "passing" condition than in the "clear road" condition. There

[9] This is the brightness of an object of 10% reflection factor illuminated by a light of 3000 candles at a distance of 1000 feet.

is thus no conflict between the two conditions as regards the effect of change of absolute intensity of the beam and no compromise is therefore called for on this account.

THE VISIBILITY AT DIFFERENT DISTANCES BETWEEN THE VEHICLES

The value of I so far considered is that in the off-side upper quadrant of the beam in a direction of which the angular co-ordinates are $\phi = \tan^{-1} d/x$ and $\theta = \tan^{-1} h/\sqrt{d^2+x^2}$, i.e. in the case considered ($h=1.5$, $d=5$, $x=100$), 2.9°, 0.86°. It is clearly possible to calculate for various values of x (up to 150 feet) the visibility which would be obtained in the "passing" condition for any given beam distribution. For the purpose of the present paper, however, it is better to invert this process and to determine limits for the candle-power at various positions in the beam, assuming for this purpose that the visibility V must not fall below some agreed arbitrary value.

The result so far obtained, viz. that V exceeds 4 with a ratio $I/I_0 = 0.1$ where the angular co-ordinates of I are 2.9, 0.86 in degrees, indicates that it will not be unreasonable to take this value of V as the lower limit upon which to base the calculations. Table 2 gives, then, for the various values of x, the maximum permissible value of the ratio I/I_0 when I_0 has various values from 2000 to 20,000 candles.

It will be seen from this table that, to a close approximation, the ratio I/I_0 is independent of x and varies only with I_0. This result enables the consideration of the desired beam distribution to be materially simplified. For it may be assumed that in the great majority of beams, the candle-power decreases from the center outwards. The governing requirement for a beam of restricted glare is, therefore, that the I/I_0 ratio should not exceed the values given in the table when the co-ordinates of I are 1.9° and 0.57°. Provided this requirement be met, the visibility in the "passing" conditions will never be less than 4 and it will probably be greater than this for all values of x less than 150 feet.

THE EFFECT OF CHANGE OF CONDITIONS

Naturally, the precise point in the beam at which the value of I is restricted depends on the values taken for h, d and l. For instance, if it were to be agreed that it was sufficient to be able to detect objects 100 feet ahead instead of 150 feet, the co-ordinates of the point of restricted I would be 2.9° and 0.86°, assuming the same values as before

for h and d. This is, probably, a much easier condition to comply with and it is therefore necessary for some agreement to be reached as to the minimum distance ahead for which visibility is required.

TABLE 2. *Values of I for which the visibility V is equal to* 4

($h=1.5$ *ft.*, $d=5$ *ft.*, $l=150$ *ft.*, $\rho=0.1$)

	I_0 (candles)	E/D^2 (c/sq. ft.)	I (candles)	I/I_0	Co-ords. of I	
					ϕ	θ
$x=25$	2,000	0.0024	210	0.105	11.3	0.37
	5,000	0.0075	656	0.13		
$\frac{E}{D^2}=\frac{I}{87,500}$	10,000	0.0184	1610	0.16		
	20,000	0.0408	3570	0.18		
$x=50$	2,000	as	205	0.10	5.7	1.71
	5,000	above	641	0.13		
$\frac{E}{D^2}=\frac{I}{85,500}$	10,000		1570	0.155		
	20,000		3490	0.175		
$x=75$	2,000	as	202	0.10	3.8	1.14
	5,000	above	630	0.125		
$\frac{E}{D^2}=\frac{I}{84,000}$	10,000		1550	0.155		
	20,000		3430	0.17		
$x=100$	2,000	as	200	0.10	2.85	0.86
	5,000	above	623	0.125		
$\frac{E}{D^2}=\frac{I}{83,000}$	10,000		1530	0.155		
	20,000		3390	0.17		
$x=150$	2,000	as	197	0.10	1.9	0.57
	5,000	above	615	0.125		
$\frac{E}{D^2}=\frac{I}{82,000}$	10,000		1510	0.15		
	20,000		3350	0.165		

All the values assumed in calculating the figures given in Tables 1 and 2 have been taken as typical of current practice. It is, however, necessary to consider the effects of likely variations.

In the first place, h has been taken as 1.5 feet, i.e., it has been assumed that the driver's eye is 18 inches above the level of the headlights. It is clear that if this distance be decreased, the glare will be

increased and the visibility lowered, partly on account of the reduction in the value of D, but principally on account of the increase in I/I_0 which may be expected to take place as θ decreases. Now it is clear that h can only be fixed for all passing cars if both the mounting height of the lamps and the height of the driver's seat are standardized. Since, however, an increase in h may be expected to produce an increase of visibility, it appears desirable first to adopt a maximum for the mounting height, and then to fix a minimum height for the driver's seat such that his eye is at least 18 inches (or whatever distance be agreed upon) above the maximum level for headlights. Unless this be done there is no guarantee that any value of h which may be adopted for the purpose of arriving at a beam specification will always be met with on the road.

The value adopted for d, viz. 5 feet, is probably not likely to be diminished much in practice. It is, however, desirable to point out here that the road has been assumed to be straight so that the two cars are travelling along parallel straight lines. This is an assumption which, unfortunately, is not by any means always fulfilled in practice. However, modern motor roads are constructed to be as straight as possible, and in the case of a winding road there is no safety device other than a reduction of speed during the period of passing.

The last assumption, and the one which is of the utmost importance, is that of exact similarity of the lights not only as regards their beam distribution but also as regards the absolute values of I and I_0. Now it is evident that any increase in I_0 will increase the brightness of the object to be discerned and therefore the visibility. At the same time, an increase in I will increase the glaring effect and therefore lower the visibility. It is clear, then, that what is required is a minimum value of the ratio I/I_0 and this must, presumably, be dictated by the possibilities in the design of optical or other apparatus modifying the beam distribution. At the same time, for any given value of I/I_0 there are three great advantages in having I_0 as large as possible. These are (i) the visibility in the "clear road" condition varies as I_0, (ii) the visibility in the "passing" condition increases slightly as I_0 increases (see Table 1) and (iii) the visibility of signs, trees, etc. on the off side of the road increases as I increases. On the other hand, for any given type of headlight it may be assumed that the power required for the headlights increases as I_0 increases.

Now it might be argued that the advantages of a large value of I_0 are such that the greatest possible value should be adopted as standard,

provided the agreed value of I/I_0 be not exceeded. Unless, however, it is reasonable to expect that the majority of vehicles would be fitted with headlights having this value of I_0, a dangerous state of affairs might easily arise. This will be seen quite readily by considering the case of a car fitted with lights having standard I_0 and I/I_0 ratio, meeting another having lights with a smaller I_0. The driver of the vehicle with the less powerful lights will clearly experience the full permissible glare from the standard lights he is meeting, while his own lights are not sufficiently powerful to provide the standard illumination. His power of discernment (V) will thus be below the value adopted as the minimum for satisfactory driving.

The only satisfactory course, then, is to specify a maximum for I which is such that, *with a practical value of* I/I_0, I_0 is not reduced below a value which it is reasonable to demand having regard to the cost, both initially and in operation. In addition it is necessary to specify a minimum value of I_0 so that the illumination of the object may be sufficient to give the necessary visibility. The maximum for I and the minumum for I_0 must be so chosen that I/I_0 has as low a value as is consistent with practical design and with the necessity for allowing tolerances in the bulb candle-power.

In this connection it is desirable to consider what is the change in visibility produced by (a) a change of ± 20 per cent in I, and (b) a change of ± 20 per cent in I_0. It has always to be remembered that the ratio governing the visibility is the ratio of the I of one headlight to the I_0 of the headlight meeting it.

It will be sufficient to consider the effect when $x = 150$ feet. If the nominal values of I and I_0 be respectively 1500 and 10,000 the normal visibility will be equal to 4 when $l = 150$ (see Table 2). Taking the limits of ± 20 per cent assumed in the previous paragraph the maximum and minimum values of visibility will respectively occur when (a) I is at its minimum value of 1200 when I_0 is at its maximum of 12,000 and (b) I is at its maximum 1800, with I_0 at its minimum 8,000. The corresponding values of V are easily calculated. They will be found to be 5.7 and 2.7 respectively. This example will serve to illustrate the importance of securing the narrowest limits possible for the candle-power of the light source.

THE DIPPING OR THE ALTERNATIVE HEADLIGHT

If all headlights are restricted to a maximum value of I which is compatible with both a reasonable value of I/I_0 and a value of I_0 at-

tainable without the use of unduly expensive equipment, the maximum value of I_0 is limited to a figure much below that in use on many vehicles. If, therefore, a driver desires to use more powerful lights when on a clear road, his need can only be met by the provision of two distinct types of lights, one for each condition. Thus it would be necessary to specify that all vehicles should be provided with headlights of the "passing" type while vehicles used for fast driving at night could be permitted to have, in addition, headlights of a much more powerful type and of a quite unrestricted beam distribution. The use of these lights would be prohibited when meeting other vehicles.

It might be found possible, by ingenuity in optical design, to produce a single headlight which would serve both purposes, i.e. one in which the

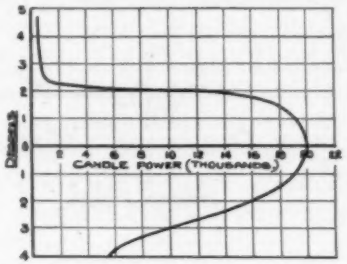

FIG. 4.

ordinary beam was of high candle-power while, by tilting, or by switching over to another lamp or filament, a beam of the standard "passing" type could be obtained. A simple dip of the ordinary headlight beam does not produce the required result since, in order to reduce the value of I to below the specified maximum, the axis of the beam must be depressed some 2 to 3 degrees with the result that objects more than 75 feet ahead of the car are very poorly illuminated. A distribution such as that shown in Fig. 4 could be used for both passing and clear road conditions, a tilt of 2 degrees being required for the former.

THE EFFECT OF THE NEAR-SIDE HEADLIGHT

So far only the effect of the off-side headlight has been considered, but it is easy to compute the effect of adding a similar headlight on the near side. If the distance between the headlights be 4 feet and the

values of h, x and ρ be as assumed in Table 2, the value of V is found to be between 6.2 and 6.4 instead of 4.[10]

THE AMERICAN SPECIFICATION

Since the only specification which has been adopted for a beam of reduced dazzle is that produced in America and referred to above, it is interesting to examine the degree of visibility which should be obtained, assuming all vehicles to be fitted with lights to this specification. Fig. 5 shows the candle-power limits prescribed for the combined beam of the two lights. For ease of calculation it may be assumed that the combined beam is produced by a single headlight situated mid-way between the two actual headlights. It will be seen that the axes of the beams are tilted downwards about 1 degree. They therefore strike the ground at a distance of about 144 feet ahead of the lights if these be mounted at 2

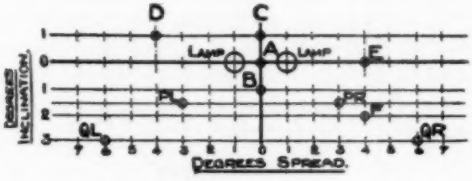

FIG. 5.

feet 6 inches. Assuming, however, that the lowest parts of an object 150 feet ahead are illuminated by a beam of at least 15,000 candles, it will be seen that the brightness is 0.021 candles per square foot if $\rho = 0.1$. The maximum value of I when $x = 100$ feet, (i.e., when $\theta = 0.86°$ and $\phi = 2.85°$, see Table 2) is about 1500, so that $E/D^2 = 0.018$ and $\delta B = 0.0035$. Thus $V = 6$. When $x = 150$ ft., however, I may be as much as 2500 ($\theta = 0.57°$, $\phi = 1.9°$), so that $E/D^2 = 0.030$, $\delta B = 0.0055$ and V is only 3.8. The values taken for I are only very approximate since no figures are specified between the points (0°, 0°), (0°, 1°), and (4, 1°). The above example will, however, serve to show the order of the effect to be expected with such a specification.

THE EFFECTS OF LOADING AND OF ROAD CONVEXITY

Since the vertical angle between the directions in which I and I_0 are measured is less than one degree, great accuracy is necessary in the

[10] The additional assumption has been made that the effect of a number of glaring sources in the field of view is equal to the sum of the effects due to each separately.

vertical adjustment of a headlight beam. Such adjustment is now quite practicable but it may easily be rendered quite ineffective by a loading of the car which causes an upward tilt of the beam. There is a need for some method of supporting the lights which shall render the direction of the beam axis as independent as possible of the car loading.

Another important factor, for which there would seem to be no remedy, is the rise of the beam caused by a convex curvature (in the vertical plane) of the center line of the road. Only a reduction of speed will reduce the danger due to this condition.

REARWARD ILLUMINATION

There is a possible method of increasing the illumination of objects immediately to the rear of an approaching vehicle without increasing the glare suffered by the driver of that vehicle. If a projector giving, say, 1000 candles in the rearward direction (but slightly inclined to the off side) were mounted at the back of the vehicle, objects at 50 feet or less to the rear would be illuminated sufficiently for them to be picked up without the use of powerful headlight beams. If each of two opposing vehicles were so equipped, the region illuminated by each rearward projector would travel towards the driver of the opposite vehicle in such a manner that he should be able easily to detect objects ahead of him for a considerable distance.

Confusion with ordinary forward pointing headlights could be avoided by coloring the rearward beam a distinctive red. This would involve the use of a 4000 candle beam with a red glass of 25 per cent transmission. Further, to prevent dazzle to the drivers of following vehicles, a mounting height of 3′6″ and a downward tilt of 4° could be adopted as it would only be necessary to illuminate some 50 feet of roadway.

It is suggested that an alternative solution of the glare problem might be found in the adoption of such lights instead of the "passing" lights chiefly considered in the principal part of this paper.

It would seem that a reasonable specification for such lights should be that they should have, over a given portion of the beam, a candle-power equal to a specified fraction of the candle-power I of the main headlights carried on the same vehicle. The value of I would naturally be measured in the direction of the eye of the driver of an opposing vehicle at a distance of 100 feet, since it is supposed that the rearward beam is powerful enough to give the necessary illumination for a further 50

feet behind the vehicle which carries it. This direction is, therefore, 0.86 degrees upward and 2.85 degrees to the off-side of the axis (see Table 2). It should not be at all difficult to design a headlight to give a beam in which the fraction I/I_0 (I being defined afresh as just described) does not exceed 0.3. If, then, the standard of visibility demanded be that which is obtained when I/I_0 equals 0.1 the total illumination of the object must be equal to that which would be provided by a beam of axial candle-power 3 I_0, i.e., the illumination produced by the rearward beam at a distance of 50 feet must be equal to that produced by a beam of candle-power 2 I_0 at a distance of 150 feet, i.e., the candle-power of the rearward beam must be equal to 0.22 I_0.

The use of a distinctive yellow light in place of red would enable the power consumption of the rearward projector to be considerably reduced, since a distinctive yellow coloration, sufficient for discrimination from white, can be obtained with a glass which transmits at least 50 per cent of the incident light so that the candle-power 0.22 I_0 found to be necessary in the case considered above could be obtained with a projector giving a beam candle-power of 0.44 I_0.

It is to be noted that the rearward light is only needed during the "passing" condition, so that adding it to the headlighting equipment of a vehicle should not necessitate a serious increase in the battery or other supply to be carried.

It will be clear that this method of overcoming the glare problem is less sensitive to the tilt of a vehicle due to loading, and to the effect of changes in road slope, than is the ordinary method. For in the latter, as has been said already, a change of level of the vehicle of less than 1 degree causes I to become I_0, i.e. the effective value of I is increased ten times. When the rearward projector is used, however, a change of level of 1 degree only increases the value of I about three times, since it is assumed that the headlight used under these conditions has a value of 0.3 instead of 0.1 for the ratio I/I_0.

CONCLUSIONS

The subject is so complicated that it may be useful here to state briefly the conclusions which can be drawn from the foregoing applications of the principles of visual efficiency under conditions of glare.

(1) When a vehicle is alone on the road, the higher the candle-power of the headlights the better the visibility.

(2) When vehicles are meeting, a specified minimum visibility may be secured by having:

(a) a specified minimum value of I_0, the axial candle-power, for the headlights of all vehicles.

(b) a specified maximum I for the value of the candle-power of every headlight in a given direction or region in the off-side upper quadrant. This direction is that of the eye of the driver of an approaching vehicle at a given distance. The value of I/I_0 should be as small as possible, but it probably cannot be reduced below about 0.1 since the angle between the directions in which I and I_0 are measured is very small;

(c) a specified maximum value for the mounting height of headlights, and a specified minimum for the height of a driver's seat. By this means a certain minimum value is secured for the height of the driver's eye above the level of the approaching vehicle lights.

(3) The value of I_0 chosen under 2(a) above should be as great as possible, consistent with the requirement that headlights giving this value of I_0 must be carried by all vehicles (or all vehicles of a given class or liable to travel at more than a given speed).

(4) If a driver wishes to have a more powerful light than that allowable under (2) in order to secure better visibility on a clear road, two sets of lights may be carried. One set is then unrestricted in candle-power but must be put out when within a specified distance of a vehicle approaching from the opposite direction. The other set must conform with the requirements of paragraph (2) and must be used when meeting another vehicle. Alternatively, it may be possible to combine both types of beam in a single headlight by the use of a special form of dipping device. The ordinary dipping beam does not produce the results specified.

(5) If a suitable projector be fitted to the back of a vehicle so as to illuminate objects to the rear, the ratio I/I_0 described in paragraph (2) may be very materially increased, say to 0.3. This projector may give a beam of distinctive color, red or amber, and is for use only when meeting other vehicles. The effect of uneven loading of the vehicle is much less for this system than for the system described in paragraph (2) and it might prove possible, by the use of suitably designed rearward projectors to avoid the use of a restricted headlight beam altogether. More experiment on this matter is needed, however, before it is possible to decide this definitely.

NATIONAL PHYSICAL LABORATORY
TEDDINGTON, MIDDLESEX, ENGLAND.
NOVEMBER 1928.

ON THE BLACKNESS OF BLACK BODIES AND THE ILLUMINATION OF LIGHT WELLS

By H. Buckley

The author* has recently been investigating the distribution of radiance on the inside walls of a number of uniformly heated enclosures, taking into account the inter-reflection of radiation between the walls. In these investigations it was shown that for purely diffuse emission and reflection of radiation, the radiance at any point on the walls is given by an integral equation of the second kind which merely expresses the fact that the radiance at any point on the inside of the enclosure is equal to the initial radiance due to the thermal emissivity at the point, increased by the reflected portion of the radiation received from the rest of the enclosure. That is

$$\Theta(P)=f(P)+\lambda\int\int\Theta(Q)\cdot K(P\cdot Q)dS_Q \qquad (1)$$

where $\Theta(P)$ is the final radiance at point P on the enclosure S, $f(P)$ is the initial radiance at point P due to its thermal emissivity, $K(P\cdot Q)$ is the radiation emitted per unit area per second at Q to unit area at P when the radiance at Q is unity, λ is the reflection ratio at P, and the integration is carried out for all positions of Q on the enclosure S.

For an infinite circular cylinder maintained at the constant temperature $T°$ the integral equation is

$$\Phi(x_1)\sigma T^4=\left\{\epsilon+\frac{1-\epsilon}{4}\int_0^\infty\Phi(x)\cdot K(x\sim x_1)dx\right\}\sigma T^4. \qquad (2)$$

where ϵ is the emissivity, supposed constant throughout the spectrum, x and x_1 are distances from the end of the cylinder measured in terms of the radius and

$$K(x)=2\{1-x(x^2+6)\ (x^2+4)^{-3/2}\}$$

For two parallel semi-infinite planes having their edges parallel and in a plane normal to the planes themselves the integral equation is

* Phil. Mag., 4, p. 753; 1927.
Phil. Mag., 6, p. 447; 1928.
Int. Commission on Illumination Proc., 7; 1928.

$$\Psi(x_1)\sigma T^4 = \left\{ \epsilon + \frac{1-\epsilon}{2} \int_0^\infty \Psi(x) \cdot k(x \sim x_1) dx \right\} \sigma T^4 \qquad (3)$$

where x and x_1 are in terms of the distance apart of the planes and

$$k(x) = (x^2+1)^{-3/2}$$

In the former case if the end of the cylinder be closed by means of a circular disc of emissivity unity and consequently of reflectivity zero, at the same temperature as the walls of the cylinder, the cylinder will approach the thermodynamic ideal of a constant temperature enclosure. Hence the radiation from every point will be complete or black body radiation, i.e., σT^4.

Thus the effect of closing the open end of the cylinder by means of the disc is to increase the radiance at every point from $\Phi(x)\sigma T^4$ to σT^4. Hence $\{1-\Phi(x)\}\sigma T^4$ which is the "defect from black body radiance" is the difference between what the walls radiate when the end disc is in position and what they radiate when it is not in position. What they radiate in each case is the radiation corresponding to their emissivity increased by inter-reflections between the walls alone, since the end disc has zero reflectivity. Hence the defect in black body radiation is equal to the radiation from the walls due to the radiation received by them from the end disc, increased by the inter-reflection between the walls.

The same argument applies if the end disc is replaced by an infinite disc having the same properties as the end disc, but removed to an infinite distance. It also applies if the cylinder is not self radiating, since what the walls radiate due to the presence of the disc is independent of what they radiate on their own account.

If now the infinite disc be replaced by a uniform diffusely radiating sky of radiance B, the sky can be regarded as having zero reflectivity so that the same argument applies if σT^4 is replaced by B. Hence the radiance of the walls of an infinite cylinder of reflectivity ρ, i.e., $(1-\epsilon)$, when illuminated by a uniform sky of radiance B is given by

$$\{1-\Phi(x)\}B$$

where $\Phi(x)$ is given by equation 2.

In the similar case of the two parallel semi-infinite planes the radiance at any point when they are illuminated by a uniform sky of radiance B is given by $\{1-\psi(x)\}B$ where $\psi(x)$ is given by equation 3.

The results given above have been derived on the assumption that the emissivities and consequently the reflection factors of the enclosures are constant throughout the spectrum. If the emissivity is not constant the same results will still apply for each wave length interval if the suitable value of the emissivity is used and Wien's or Planck's expression for the energy distribution is substituted for σT^4. In this case the defect of black body radiance is a function of wave length so that the effect of an aperture is to make the enclosure a selective radiator, while for constant emissivity the aperture makes the enclosure a "grey" radiator.

The argument by which these conclusions are obtained is quite general and applies to enclosures of any shape with any number of apertures of arbitrary shape so long as the enclosures are uniformly heated and are illuminated by a uniform diffusely radiating sky. Hence it follows that considering black body radiance as the unit, the defect in black body radiance at any point in a uniformly heated enclosure is numerically equal to the radiance at the same point when the enclosure is not self radiating but is illuminated by a sky of unit radiance.

This relationship between the defect of black body radiation from an enclosure and the radiance of the same enclosure illuminated by a uniform sky applies also to the state of polarisation and of diffusion of the radiation in each case. Black body radiation is unpolarised so that if the radiation from an enclosure is partially polarised the defect of black body radiation will be partially polarised in the opposite direction and the radiation from the enclosure when illuminated by a uniform sky will be similarly polarised.

In consequence it is possible to deduce from brightness measurements in scale models illuminated by artificial skies, what is the defect in black body radiance in enclosures of any given shape. In the cases of the infinite cylinder and the two parallel semi-infinite planes the results of calculation are available also, so that it is possible to check the method in these two instances.

It happens that an investigation of the efficiency of light wells of different forms and reflection characteristics is being carried out at the National Physical Laboratory on behalf of the Illumination Research Committee of the Department of Scientific and Industrial Research, so that numerical data are at hand.

The investigation has been concerned with model light wells illuminated by an artificial sky having a brightness of about 15 candles per

square foot. Brightness measurements were made by means of a Macbeth Illuminometer. The two types of light well on which measurements were available were: (1) a light well of square section $6''\times6''\times60''$ (deep); (2) a light well of rectangular section $6''\times60''\times60''$ (deep).

Observations were made down the middle of a $6''$ side in the former case and down the middle of a $60''$ side in the latter. The sides of the light wells were sprayed with matt white or grey paints which were fairly neutral in color.

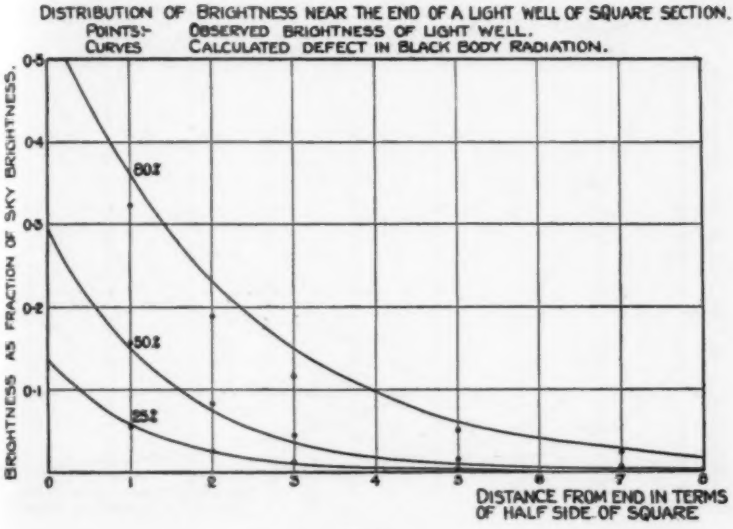

FIG. 1.

Neither of these types of light well corresponds exactly to either of the two enclosures for which the functions $\{1-\Phi(x)\}$ and $\{1-\psi(x)\}$ are known by calculation, but it has been assumed that the former case is equivalent to a circular light well having the same cross sectional area and that the latter is equivalent to a pair of parallel semi-infinite planes.

The results of calculation and experiment are shown in figs. 1 and 2 for values of the reflection factor of 80%, 50.0% and 25.0% for the calculated results, i.e., the curves, and of 80%, 52.5% and 24.5% for the experimental results, i.e., the isolated points. From these it can be deduced that there is a fair agreement between experiment and

calculation. It should be pointed out however, that the results of experiment on what was regarded as an approximation to two parallel semi-infinite planes should be increased by about 10%. The evidence for this was found by examining the brightness measurements on a series of light wells of rectangular cross section varying from $6'' \times 6''$ to $6'' \times 60''$. It appeared that the results were approaching a limiting value as the length of the light well was increased, and that for the light well of cross section $6'' \times 60''$ the observed values were about 10% less than the limiting value.

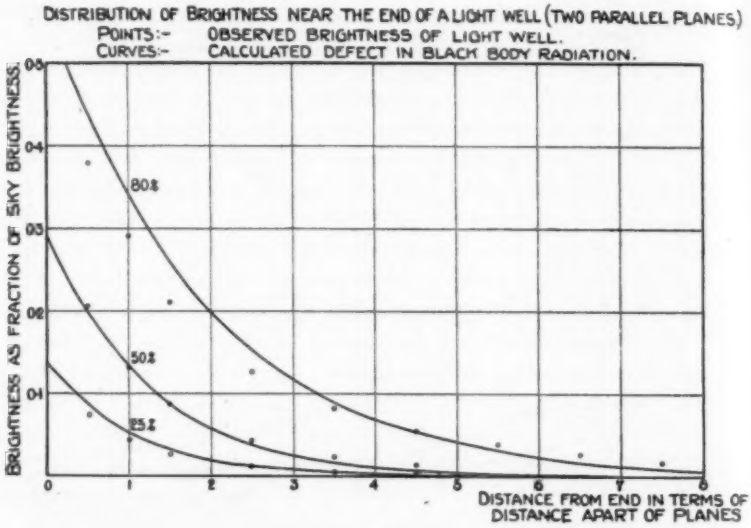

FIG. 2.

It will be noticed that for values of the reflection factor of 80% the observed values at the end are less than the calculated ones and that generally at points removed from the end the observed values are greater than the calculated ones.

It is not possible to state what is the cause of this difference as the calculated and experimental results refer to enclosures of different shape, but in view of the increased reflection factor which practically all diffusing materials exhibit at high angles of incidence the higher values obtained by experiment at points removed from the end are not surprising. Another possible cause may be the fact that most grey or white paints are slightly colored so that their reflection factors are

somewhat greater for light which has been previously reflected than for the initial light itself.

It was decided, however, that experiments on an actual cylinder would be more satisfactory so that departures of experiment from calculation could not be attributed to the departure of the form of the light well from that to which the calculations referred. The results are given in fig. 3 for reflection factors of 85% and 73.5%, which being high reflection factors should provide a considerable amount of inter-reflection and a more critical test of the calculations than low

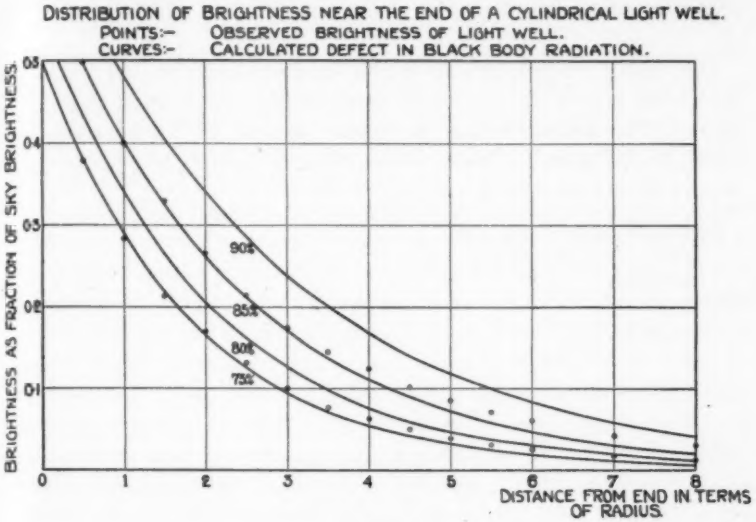

FIG. 3.

reflection factors. The curves refer to reflection factors of 75%, 80%, 85% and 90%. The agreement between calculation and experiment is very close, particularly at distances from the end up to three times the radius, after which the experimental results as before become higher than the calculated ones. The difference is not so great however, as is at first sight indicated, for if the results for the reflection factor of 85% be compared with those calculated for 85% and 90% at about six times the radius from the end, it will be seen that the observed values correspond to a reflection factor of about 87%. In the same way the results for the reflection factor of 73.5% at the same distance from the end correspond to a reflection factor of about 78%.

SUMMARY

It is shown that the effect of an aperture in the walls of a constant temperature enclosure of arbitrary shape is to produce a defect from black body radiance at any point which is equal to the radiance at the same point of the enclosure when not self radiating but illuminated by a uniform diffusely radiating sky of unit radiance.

It thus becomes possible to determine the defect from black body radiance in any specified enclosure by means of brightness measurements with an illumination photometer on a scale model of the enclosure when illuminated by a uniform diffusely radiating artificial sky.

The results of such measurements are given and compared with the calculated results for two cases which submit to mathematical treatment. The author wishes to thank Messrs. H. F. Meacock and G. E. V. Lambert for their careful work in making the photometric measurements used in this paper.

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OPTICS AS SEEN BY A PSYCHOLOGIST*

By Leonard T. Troland

I

When I was first asked to speak upon the topic which is indicated by the title of this paper, I felt that it was too general to permit of any very interesting or informative remarks. However, as I pondered upon the matter, I realized that the title in question could provide a text for a review of the very problems which have interested me the most from the beginning of my scientific and technical work down to the present time. These problems may seem superficially to be rather diverse in nature, but running through them all I can find the fundamental theme of psychological optics.

In order that I should review the entire field of investigation which I have in mind, I must say something not only concerning *optics* as it is viewed by the psychologist, but also concerning *psychology* as it is, or should be, regarded by the *optical scientist*. I fear that many psychologists cannot see optics at all. It has become the style in psychological textbooks of a certain modern class to eliminate all discussion of *sensory* problems, and to refer the psychological reader to Helmholtz for optical instruction. The reference is undoubtedly a good one, particularly since the Optical Society published its English translation of the *Handbuch*, but it implies an unfortunate blindness on the part of the psychological writers. When psychology loses sight of optical phenomena, it has turned aside from the most definite and most fruitful data which are accessible to it. Nowhere is the nature of consciousness more clearly demonstrated than in the visual field, and the relation of mind to body receives its most perfect exemplification with respect to the optic sector of the nervous system.

However, I fear that students of *optics* at large may be even blinder to the nature and the importance of *psychology* than the average psychologist is to the significance of optics. If we are to see how optics appears, or should appear, to the psychologist, we must first establish the point of view of *psychological science* itself. This is not an easy task

* Paper presented at the Washington meeting of the Optical Society of America, November 3, 1928.

in the light of present psychological discussion. I believe that very few researchers in optics would care to disagree with the definition of that science which has been formulated by President Priest of our Society. However, if I were to offer a similarly precise characterization of psychology, there would be a host of authorities against me, and this would be the case regardless of the nature of my definition, unless I were to make it extremely general; so general as to be of little value. This follows from the fact that psychology is divided into disagreeing camps.

It is therefore necessary for me to define the points of view of the principal ones among these conflicting psychological factions, separately, so that we can see how optics should look from these respective standpoints. It may not be amiss if I should indicate to you, incidentally, the conception of psychology which seems to me to be most acceptable. I can then show you how optics appears particularly from that selected standpoint.

II

Let us therefore consider how *psychology* appears to *psychologists*. We recognize that this appearance varies with the identity of the given psychologist. It is not the same for any two representatives of the science.

You all know that American psychological thought is torn by the contest between *behaviorism* and *introspectionism*. The struggle between these doctrines was formally initiated by John B. Watson, about fifteen years ago, and seems no nearer a conclusion today than it was at that time. The general conflict between *objective* and *subjective* interpretations of psychology is, of course, much older than the history of the American behavioristic movement would indicate, although earlier objectivists were not able to establish their points of view with the exactitude which is now possible. In general, the history of psychology has tended to make it an essentially subjective discipline, dealing with topics which have been left out of account or discarded by objective science. However, the objectivists in psychology have endeavored to *keep* these topics in the discard, and to establish a definition of psychology which will make of it a branch of physical science.

Psychological objectivists differ in the nature and degree of their objectivism. Some of them are quite thoroughgoing, rejecting subjective considerations entirely, whereas others retain some portions of

the older psychological subject-matter. Some of them formulate the problem of psychology in terms which are derived from the vocabulary of everyday speech, others use the nomenclature of physiology, while still others reduce the problem to terms of ultimate physics. In some cases, the discussion even becomes metaphysical in character. In general, the psychological objectivists substitute for the traditional notion of mind, that of *behavior*. They claim that the concept of mind is difficult if not impossible to use in scientific research, but even the notion of behavior requires considerable explanation. Behavior is not mere bodily movement, and it is usually conceived as being something more than a mechanical sequence of muscular contractions. It involves a definite relationship between a *stimulus* and a *reaction*, a specific linkage between these two factors which may enable us to predict what an animal or a human being will do under given circumstances. Consequently, the behavioristic psychologist is compelled not merely to observe and to record the movements which are executed by his subjects, but to determine the *conditions* under which these movements occur.

In general, such conditions appear to be divisible into two classes, as external and internal respectively. The former can be stated in terms of the forces which are acting upon the sense-organs, either at the present moment or a slightly previous one. The internal conditions, however, can only be expressed adequately in terms of the structure and properties of the *nervous system;* although to some extent they can be replaced by a recital of *prior* external conditions which have determined them in the life history of the given individual.

Some objective psychologists seem to be content with a statement of external conditions, either present or biographical, without seeking a detailed account in terms of the constitution of the nervous system. This policy leaves the investigator in maximally close contact with empirical data, but unfortunately results in an incomplete and unsatisfactory account. If we go on to consider the actual or possible details of the neuromuscular mechanism, we find that we are involved in a complex research, in which experiment and speculation play about equally important rôles. The nervous system is an intricate conducting network, which physically connects the external or stimulus conditions of response with the muscular mechanisms which react to them. A disturbance is initiated at a sense-organ and is propagated along the neural conductors, through numerous so-called nerve centers,

finally to reach a muscle or a gland. The motor outcome of this process must be determined by the momentary structure of the conducting system in accordance with laws that are generally similar to those which operate in an electrical network. If we knew the exact constitution of the nervous system of the given individual at the time, we could predict exactly what he would do under the influence of a determinate constellation of stimuli. It is true, of course, that the conduction of the nervous impulse depends upon many details which are different from those for simpler conducting systems. Nevertheless, the structure and processes of the nervous system must be conceived throughout as being reducible completely to ultimate physical terms and principles; at no point is any mysterious physical or vital factor concerned.

However, the objective psychologists may fall short of a complete reduction of the neuromuscular process to the motions of such ultimate physical units as the proton and the electron, being content with a description in terms of physiological concepts, such as those of the cell, irritability, and contractility. The majority of objective psychologists maintain that their science has to do primarily with the way in which the units considered by more basic sciences—such as physics and physiology—are compounded to yield the higher order processes that characterize behavior. However, they cannot avoid recognizing that the distinction between these various levels of organization is largely arbitrary, so that we have to deal, in the last analysis, with a unified *physical science* of the organism and its activities. Psychology can be regarded as one division of this science which considers the facts and foundations of specific neuromuscular response.

Now, if we consider psychology in this manner, thus establishing its characteristic viewpoint, how should the science of optics appear to the psychologist? What does he see when he looks at optics from this standpoint? Optics, according to President Priest, is "the science which deals with radiant energy, its genesis, its propagation, the effects which it suffers, the effects which it produces, and all phenomena closely associated with it." It is evident, from this definition, that the domain of optics cuts across that of objective psychology by virtue of the last two, or possibly three, clauses. Radiant energy constitutes a most important stimulus to the behavior of practically all living organisms. Even animals which possess no eye-spots may be affected by radiant energy through the media of thermally sensitive receptors. The importance of radiant energy, as a means for the conveyance of environ-

mental influences to the organism, increases with the degree of advancement of the latter along the evolutionary scale. For the invertebrates and the lower vertebrates, chemical stimuli are perhaps in most cases more potent than are optical ones; but for man the latter assume an impressively predominant rôle. In the human being, the cerebral cortex, that most massive of nervous correlation centers, is primarily a device for engineering muscular adjustments with respect to *visual* nerve currents. And, after all, psychology is concerned mainly with human rather than with lower animal, behavior.

If we trace the total process of visually directed response, regarding it throughout as a physically continuous propagation, we must say that it starts in the environment of the living organism, either at the source of the radiant energy or at the surface of a reflecting object. From these points, it passes, in accordance with the laws of physical and of geometrical optics, to the visual sense-organs. Within these sense-organs, there are certain "effects which it suffers," and "effects which it produces." Each of these categories includes processes which are of great interest to the objective psychologist. "Effects suffered" by radiant energy within the eye embrace the refractive operations which form the retinal image, as well as the absorption of energy which make possible the activation of the receptors. The "effects which are produced" include such receptor reaction and the consequent processes of afferent nerve conduction: in fact, the entire ensuent course of the neuromuscular response.

However, the psychologist who wishes to arrive at a thorough understanding of the organism in its behavioral relationship to the environment cannot confine his attention to these intraorganic effects. He must consider the total continuum of influence propagation from the light source or the object surface, to the final reaction effects. In the last analysis, this is all one complex physical stream of events. We may be concerned with the intraorganic effects only when we are endeavoring to ascertain the complete mechanism of the response; but we must know about the external stimulus energies in order to recognize and to describe the existence of the response as a definite process, at all. Thus we may first show that an animal is positively phototropic, or behaves so as to orient its body axis parallel to the lines of propagation of radiant energy and to move with its head end towards the source. It is a *second* step to disclose the mechanism which mediates this response, as in the theory of tropisms formulated by Loeb.

Consequently, the objective psychologists must "know his optics" if he is to be a good objective psychologist. He cannot even formulate the experimental facts, unless he understands the nature of radiant energy and the laws of its propagation. Unfortunately, there are a great many psychologists who have much to learn in this regard. The planning of psychological experiments and the recording of experimental conditions have too frequently suffered from a lack of understanding of optical principles.

It therefore seems that the objective psychologist must regard optics, firstly, as a science which furnishes him with certain fundamental concepts and principles that are indispensable to important lines of psychological research. Secondly, certain facts which fall characteristically within the domain of objective psychology itself constitute a portion,also, of optics. These are the facts of visual response. In a paper which I have previously presented to this Society, I have spoken of the "optics of the nervous system," a topic which, at first thought, seems somewhat paradoxical. However, in the paper in question, I endeavored to demonstrate the close analogy which exists between the transmission of images through ordinary optical systems, and that of pictorial representations from the retina to the cerebral cortex. Quite recently, thanks to the labor of Dr. Ives and his collaborators, we have witnessed the marvel of electrical television, but all vision is *neural* television, in the sense that it depends upon the transmission of a kinetic image from the retina to the brain along a system of physiological conductors.

III

However, the way in which optics appears, or should appear, to the psychologist cannot receive complete exposition from the standpoint of the behaviorist, for it is far from being true that the objective interpretation of the psychological problem has been successful in superceding the subjective one. The propagandas of opposing psychological schools sometimes closely resemble those of a political campaign. When we read the writings of some of the objectivists, we gain the impression that the older psychology of *mind* is quite obsolete and gone forever. However, the many representatives of subjective psychology, who still live and flourish, are apt to treat behaviorism as an upstart or as a psychological non-entity.

Psychology, for the introspectionist, may be said to consist in the study and description of "mental phenomena," which are conceived as being distinct from the facts of physics and, indeed, of all objective science. Mental phenomena are supposed to constitute a class, *sui generis*, set apart from everything which is considered by physical or physiological inquiry. Biology is properly regarded as being a strictly objective discipline, a branch of physical investigation which deals with living structures and their processes. The problems of objective psychology or behaviorism are viewed by the introspectionist as being solely biological and hence as entirely non-psychological in nature. They are all matters of the statics or the dynamics of the physical organism. Fundamentally, they involve nothing but details or aspects of a physico-chemical machinery.

Now, the objective psychologist replies to these propositions by questioning the reality, the accessibility or the importance of the so-called "mental phenomena." He doubts whether such phenomena can actually be demonstrated scientifically. He asserts that they are less clearly conceived and are less amenable to investigation than are the facts of neuromuscular response. These are his grounds for rejecting the classical, subjective definition of psychology. The subjective psychologist must respond to these objections by endeavoring to make clear the nature of "mental phenomena" and to establish their importance and amenability to scientific treatment. I confess that I sympathize with the *subjective* psychologist in this argument and disagree most heartily with the behavioristic position. Hence, I shall present the case for subjective psychology in terms which I personally approve.

The phrase, "mental phenomena," or its equivalents, has been interpreted in numerous different ways during the history of psychological research. Originally, it was supposed that a clear distinction could be made between mental and physical phenomena. The facts of the external world, as we see, hear and feel them, were taken to be directly physical, whereas the data of the internal world were classed as psychical or subjective. However, it was soon recognized that the distinction between "external" and "internal" is far from being identical with that between "objective" and "subjective." A stomach ache is an internal phenomenon, while an object which we see is external, but both of these facts can be regarded either as subjective or as objective. The gastric pain has a physical cause, while objects which we see become

parts of experience only by virtue of action upon an internal organ known as the cerebral cortex.

Philosophical psychologists have therefore endeavored to establish the idea that subjective facts consist essentially in a *relationship* or a *process*, rather than in substantial phenomenal data. Such a relationship was designated as *awareness* or, sometimes, as consciousness. It was assumed that there exists a self or ego which comes into contact with its environment and cognizes or knows the latter. The ego is also supposed to act upon the environment in processes of volition or will. Between cognition and volition (conation), there may be interpolated certain characteristically subjective processes of feeling or affection. All of these hypothecated relationships or activities were distinguished from phenomenal data, either internal or external.

Some of the behaviorists maintain that they cannot understand what is meant by mentalistic concepts, such as those of consciousness, sensation and feeling. Now, I am quite in sympathy with their difficulties if these concepts are interpreted in the manner just suggested. The notion of awareness or of consciousness, as being a relationship between a supposed ego and the world, is entirely undemonstrable and has meaning only as a logical formula. In this sense, consciousness certainly does not exist. Nevertheless we are *not* therefore compelled, by any means, to agree with the objectivist's position. We are still faced by a great mass of phenomena and by a number of distinctive problems which are not intentionally or adequately considered by any physical science. Suppose that we have worked out the entire mechanism of visual response in physiological or fundamental physical terms. At what point in this mechanism do we find the phenomenon known as *color*?

Perhaps, when a physicist thinks carelessly, he may identify color with wave length or wave length composition; but the fallacy of any such identification is revealed at once under psychophysical analysis. Infrared or ultraviolet radiant energy is just as characteristic in wave length composition as is the radiant energy of the visible spectrum, but it has no color. Color is therefore a fact which may be *correlated* with wave length but cannot be identified with the latter. It should be clear to any logical thinker that corresponding properties of identified things must be exactly similar, but there is nothing wavy about a color nor anything intrinsically colored about a wave length.

This argument which applies to color can be repeated for musical tones and for noises. It applies also to phenomenal warm and cool,

hard and soft, sweet and sour, and in fact to all of the characteristic qualities of the external world, as we know the latter directly in experience. These qualitative phenomena are not, in themselves, physical. It is mainly a matter of moving from one portion of experiential space to another to include under the same judgment the internal phenomena which we call pain, pleasure, organic sensation, kinaesthesis and so forth. Thoughts and imaginations are merely faint presentations, which have the same general character as the more vivid facts of experience that we have just considered. The phenomena of feeling and will can be reduced to similar terms.

Now, suppose that we forget the adjective, "mental," and class all of these items together and designate them merely as *phenomena*. No justifiable excuse can be advanced for labelling certain of them as mental and others as physical or non-mental. In the last analysis, none of these phenomena can be identified with physical entities, relationships or processes; and they are all equally dependent upon physiological activities in the central nervous system of the given observer. From this standpoint, a phenomenal ship which I may see upon my phenomenal horizon is just as subjective as is my thought concerning the ship. Neither of these things can be described in terms of protons, electrons or other physical units. Consequently, it seems reasonable to deliver unto psychology what is properly psychology's, namely the sum-total of all phenomena, as actually and immediately given. This is a distinctive subject-matter, touched by physical science only to be thrown into the scientific discard, and yet it is the most vividly real subject-matter with which any science is presented.

The sum of all actual phenomena in the above sense, constitutes what is commonly called *experience*, upon which all empirical science is supposed to be founded. However, physical science is an attempt to explain or to account for certain kinds of experience, namely those representing an external world which is independent of any particular observer. Psychology takes experience itself as its problem, and is not concerned primarily with its interpretation or the discovery of its objective conditions. Moreover, the psychologist quickly recognizes a fact which the physicist usually neglects, namely, that experience exists only in the form of individualized spheres or fields of consciousness: your experience or mine. We have no grounds for believing that experience extends beyond such concrete individual loci. While physical science substitutes molecules, atoms, radiation quanta, etc., for the

actual phenomena, psychological analysis endeavors to express experience in terms of the elements of experience itself. Psychology thus becomes the empirical science *par excellence*, so that, instead of dealing with a subtle and fugitive subject-matter—as some critics claim—it is the exclusive custodian of the direct facts upon which all scientific developments must be founded.

How, from this standpoint, must optics appear to the psychologist? In answering this question, we may turn to the final clause of President Priest's definition of optics, which refers to "all phenomena which are closely associated" with radiant energy, as falling with the domain of optical science. Now, if the word "phenomena" in this definition is to be interpreted in the sense in which we have already used it above, some of the data of subjective psychology must also fall within the domain of optics. This, indeed, is explicitly taught in President Priest's discussion of his definition. Optics, according to his view, is not a narrowly circumscribed subdivision of physics, but on the contrary, it intersects all of the major scientific classifications.

The association of optics with those psychological data which we call the *phenomena of vision* is more fundamental than any other feature in the definition of optical science. Historically, optics itself is defined by virtue of this association, alone. It is the science which deals with the physical entities and processes which are involved in *vision*. The primitive optical investigator started with color (including brilliance) and the properties of subjective visual space, evolving the present doctrines of physical optics only by a laborious line of reasoning, continuing for many centuries. Eventually, the consequences of this reasoning—the theory of radiant energy—became so impressive that they have almost overshadowed the actual phenomena upon which the whole scientific development has been based.

It is still permissible, however, to speak of a *psychological* optics, from the standpoint of purely subjective psychology. This branch of optics is, in my estimation, one of the most interesting and fruitful departments of purely introspective research. The visual section of human experience is more persistent, more clearly organized and more complicated than is any other phenomenal department. Blindness means a greater loss of experience than does any other single psychophysiological defect. It seems highly probable that a thorough understanding of visual phenomena will provide us with the fundamental principles which apply to all subjective facts. Much remains to be

accomplished in this domain, from the purely introspective angle. The subjective study of color, not only as to its fundamental attributes of hue, brilliance and saturation, but in respect to those nuances which the German psychologists call *Erscheinungsweisen* (or modes of appearance) offers a fascinating field for investigation. The properties of purely subjective visual space have thus far received scant attention, but the German *Gestalt* psychologists are reaping a rich harvest from their researches upon visual "configurations."

IV

However, there is still another interpretation of the psychologist's problem, and this is the one which seems to me to be the most interesting and significant of all. We do not need to limit the task of psychology to a consideration of the bare introspective facts; we may extend it to include a study of the *relationships* between phenomena and the world of physical science. This is, of course, the subject-matter of what is commonly known as *psychophysics* or *psychophysiology*. It is suggested by President Priest's idea of an "association" between certain phenomena and radiant energy, the phenomena being psychical and the energy purely physical. This defines the domain of psychophysiological optics or, visual psychophysiology.

I have said that I am opposed to the strictly behavioristic interpretation of psychology, and thus that I favor the subjectivistic conception of the science. However, I am inclined to agree with the behaviorist's feeling that a *purely* subjective method of inquiry must remain relatively unfruitful. In order that the results of psychological research should possess maximal significance, they must establish a correlation between phenomena and physical facts. Such a correlation should make possible the control of phenomena, and hence of human experience in its totality, by appropriately guided manipulation of its physical determinants.

Now, it may seem that physical investigation, alone, should automatically establish such correlations, and this is actually the case to some extent. However, physics in its modern form appears to have thrust the consideration of these relationships to one side, on account of its exclusive interest in the physical interpretations, *per se*. The physicist recognizes that certain colors are associated with certain wave lengths, but he is concerned, intentionally, with the wave length rather than with their color relationships. Enlightened physicists have definitely passed this sort of relationship over to psychology.

However, this is not the whole story. Investigation shows that the psychophysical correlations which are established incidentally to physically directed research are neither reliable nor fundamental. Color (hue) has no inviolable relationship with wave length. The wave lengths, 670–700 mμ, may ordinarily yield *red*, but I find no difficulty, in my laboratory, in-making them produce very good purples, blues or blue-greens. It is quite easy, also, to evoke colors without the use of any radiant energy, whatsoever. They may be associated with the passage of an electrical current through the eyeball, with pressure upon the retina or with a state of malnutrition of the visual cortex of the cerebrum.

The psychophysics which develops naturally as a by-product of physical investigation, associates phenomena with *stimuli*, or with objects outside of the organism. Intentional psychophysics, or psychophysiology, however, is concerned with the establishment of *direct and reliable* determinants of phenomena, and investigation shows that these must be sought inside, rather than outside, of the individual organism. It is true that numerous physicists, such as Kepler, have recognized the existence of such correlations, but it does not appear to be a natural part of physical research to trace out their details. Consequently, this problem seems to fall into the lap of psychology. Not only is this so, but it appears to me that psychophysiological conclusions constitute the essence of what is permanently valuable and scientifically progressive in the history of psychological research, as a whole. Purely introspective analysis is to a large extent merely common sense report, and its technical elaborations are frequently barren of further significance. Behavioristic studies, on the other hand, belong properly in the domain of purely physical science.

The study of the detailed way in which our phenomenal experience is determined by the operations of the nervous system is a unique line of inquiry, dating from the beginnings of experimental psychology, and having still a long distance to go, but one which has tremendous human importance. I have endeavored to present the fundamentals and main results of this type of investigation in my forthcoming book entitled *The Principles of Psychophysiology*.

From the standpoint of psychophysiology, *optics* assumes an impressive aspect. The whole of visual psychophysiology must be regarded as a subdivision of optics in general. It is also, without doubt, the best developed and most fruitful department of psychophysiology

itself. One has only to consider the contents of the three volumes of Helmholtz's Optics to gain some impression as to what is contained within this domain. However, I do not wish you to interpret me as regarding psychophysiological optics as being, at the present moment, in a satisfactory state. It is a field in which the investigator who is adequately equipped as to optical knowledge and apparatus, can bring forth results of fundamental importance. I am confident that the efforts of certain contemporary workers will soon provide us with a really new insight into some of the fascinating mysteries of human vision. I only hope that these workers will not neglect the psychophysiological aspect of their problems, that they will not be too strictly objective or physiological in their interests.

Optics was originally defined as the *science of light*, but modern illuminating engineers recognize that light is a psychophysiological entity. The concept of photometric intensity involves an evaluation of radiant energy in terms of its capacity to produce brilliance, an attribute of the subjective phenomenon which we call *color*. Although modern optics has transcended the older definition and has come to deal with invisible, as well as with visible, radiant energy, its predominant interests are still in those rays which affect the human optical sense-organs. If we are to arrive at a satisfactory understanding of light, we cannot neglect its phenomenal and neurological aspects. The tremendously significant physical researches of such men as Michelson—whom we honor in this meeting—must be supplemented by further delving into the mysteries of visibility, visual acuity, flicker and colorimetric functions. The time is ripe for a new and systematic attack upon some of these relationships which have received no adequate experimental treatment since the time of Helmholtz and König. I may refer, as an example, to the case of the trichromatic excitation functions. Why should we not have a statistical determination of these curves which is as reliable as is that which has been developed for the visibility function?

Some time ago, I was requested by a committee of the National Research Council to attempt a theoretical computation of the minimum illumination which should suffice for maximally efficient industrial operations. Such a computation would be possible if all of the psychophysical functions which are obviously involved were known with a reasonable degree of precision. Work has been done upon every one of these functions, but the practical utilization of the results

proved to be impossible, because of failure to specify conditions accurately and because of inconsistency between the findings of different investigators. There are many practical questions, of great human importance, which could be answered reliably if the psychophysical science of vision were in a more advanced state.

However, from my point of view, there is no field of scientific investigation which is as fascinating for its own sake, as is psychophysiological optics. We are dealing, here, with the conditions under which our principal impression of the external world about us is formed. We project this phenomenal impression, intellectually, into a permanent cosmos, but we know that it is actually determined by physiological activities in our own brains. The majority of our physical concepts are based upon visual perceptions or imaginations, yet this whole system disintegrates when the processes of the occipital cerebral cortex become deranged. The occipital cortex itself, however, is a physical concept. When we have penetrated to the bottom of this mystery, we shall have unravelled many tangled skeins of scientific and philosophical thought. The results may constitute a perfection of psychological knowledge, but the progress of the research will be possible only through an application of the principles and instruments of optics.

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SOME OF THE PHYSIOLOGICAL EFFECTS OF RADIANT ENERGY[1]

By Henry Laurens

Generations of laymen and physicians have somehow assumed that part of the beneficial effect of an outdoor life is attributable to sunshine. In early times light inspired religion rather than science, but the value of sunlight as a therapeutic agent has been known for centuries. The Babylonians, Assyrians, Greeks, and Romans used sunbaths. In the ninth century smallpox was treated with red light, the Incas treated syphilitics by heliotherapy, and in Italy sunlight was used to disinfect clothes infected by the plague.

Although heliotherapy is probably the oldest form of therapy, no clear scientific definition of the relationship between sunlight and health was made until the later years of the last century when, as a result of clinical observation and of experiment, it was established that "light treatment" is excellent for many abnormal conditions, such as extrapulmonary tuberculosis, rickets, tetany, chronic anemias, various skin diseases, wounds and so on.

There is little, if any, reason for supposing that the growth of the higher animals is dependent upon light, although light may exert potent physiological effects when appropriate conditions for its influence present themselves. When the diet is adequate the lack of daylight seems to exert no detrimental influence but when the diet is even slightly unbalanced, particularly as to the minerals calcium and phosphorus and the vitamins A and D, the effect of the lack of radiant energy on physical well-being and nutritional condition is evident. Screened as man is by window glass, clothes, fog, and smoke, he is cut off from the shorter wave lengths of sunlight for a considerable period of the time. Besides he spends much time indoors in the heated stagnant air of rooms and thus suffers from the lack of open air and exercise. His diet is frequently deficient and unbalanced and so his resistance is lowered.

Climate in its relationship to health is not merely a question of radiation, but of radiation, fresh air, wind, temperature, altitude,

[1] Read at the Michelson Meeting of the Optical Society of America, Washington, November 3, 1928.

humidity, and so on. Man flourishes more or less in all zones, but the white races certainly show more mental and physical vigor in the temperate zones and all races seem to flourish best in moderate sunshine and in dry air, though many strong races (such as the Scotch, the Irish and the Swedes) live in comparatively moist and sunless climates. On the whole too much light and warmth is more detrimental to man than too little, and, if his diet be adequate, he maintains full vigor with very little light indeed.

There is a common belief that the hygienic and curative action of solar and artificial radiation is solely, or mainly, due to the ultraviolet fraction, while the infrared fraction is supposed to be best for some conditions; swollen joints, sprains, strained muscles and so on, and our magazines are full of advertisements describing ultraviolet lamps and infrared lamps. The outstanding influence of ultraviolet has been demonstrated in but few instances, such as the cure and prevention of rickets, the formation of melanin in the skin, the treatment of skin tuberculosis. There are some who go so far as to state that ultraviolet energy of a given range of wave length has never been demonstrated to be capable in and of itself of preventing rickets or nutritional deficiencies. Be this as it may, there is considerable evidence that the effects on many conditions, such as extrapulmonary tuberculosis (involving glands, bones, and joints), arthritis, secondary anemias, and so on, are due to the entire spectrum from ultraviolet to infrared.

The question as to why in artificial phototherapy this or that source should be used will not be dwelt upon here. In passing, it may be remarked that, in general, the flaming carbon arc is to be preferred to other sources because the energy emitted by it is more like sunlight than that from any other source. The advantage of the mercury lamp is its richness in ultraviolet wave lengths shorter than those occurring in sunlight. Some of the cored carbons now obtainable are said to emit an even greater percentage of such ultraviolet than the mercury arc in quartz.

The skin is the means of contact with the outer world and not simply a protection. It is an organ with nervous, excretory, circulatory and nutritional functions. Its appearance after an unusual exposure to sunlight or to artificial radiant energy is familiar to every one. The almost immediate reddening is due to radiant heat and disappears soon after the irradiation. It is followed in a few hours by inflammation due to the action of the ultraviolet rays. The usually diffuse and homo-

geneous redness of this inflammation is confined strictly to the irradiated part and, according to the intensity of the radiation, may be combined with blistering and hemorrhage. The dermatitis, the end result of aggregation of particles in the protoplasm, is a pathological outcome of the skin's physiological reaction to the stimulus. By appropriate irradiation an apparently lifeless, toneless, flabby skin may be changed to a soft, velvety, colorful one.

The reddening and subsequent tanning are the results of the action of the ultraviolet in the sun's spectrum but the other wave lengths favorably influence the extent and duration of the pigmentation, since pigment produced by sunlight is of better quality and lasts longer than that produced by either the mercury or the carbon arc. Sunlight through glass which absorbs wave lengths shorter than between 320 and 330 mμ produces only a slight degree of pigmentation.

The general view is that the skin pigment reduces the action of long waved ultraviolet and increases the absorption of visible and infrared by the basal cells of the epidermis. Pigment affords no protection against radiation shorter than that found in sunlight since these wave lengths do not penetrate to where the pigment is located in the skin. While pigment may be an index of the progress of treatment in e.g., extrapulmonary tuberculosis, it does not seem to be necessary to the cure. One group of clinicians, represented by Rollier at Lausanne, Switzerland, and LoGrasso at Perrysburg, New York, lays great stress on pigmentation, regarding as poor risks those who do not pigment well. Another, represented by those at the Finsen Institute at Copenhagen, avoids pigmentation by irradiating at long intervals and seeks to produce by massive doses as severe an inflammation as possible.

Guillaume (1926) is opposed to the view that the epidermal melanin acts as a protection against the action of ultraviolet. The lesions produced by ultraviolet show that the damage is outside of the pigment; that is, between the pigment screen and the source of radiation. Guillaume cites experimental results which show that the resistance following exposure to sunlight is of much shorter duration than the pigmentation produced thereby. The resistance to ultraviolet is thought to vary directly with the thickness of the horny layer and the protection against ultraviolet is thus purely an epidermal process. Since all of the ultraviolet is absorbed before it reaches the basal epidermal layers, pigment has nothing to do with stopping it. But the skin pigment does protect the organism against excessive visible radiation and to a certain extent perhaps against infrared.

The question of the penetration of the therapeutically active ultraviolet rays has been reopened during the past few years. In general it seems that the penetration of ultraviolet is greater than given by Hasselbalch (1911). But these rays do not go very far and their essential action is one that is carried out in the outermost layers of the skin. Pauli (1927) has recently demonstrated that the application of a mixture of glycerin and alcohol to the skin will materially increase the penetration and the erythema produced in a given time. von Baeyer and Dittmar (1928) report that the application of soft soap increases the erythema produced by sunlight and the mercury arc.

Massive doses of flaming carbon arc radiation lower blood pressure to a greater or less degree, so that irradiation of this sort may represent a form of treatment for some types of hypertension. Decreases in blood pressure averaging between 8 and 10 per cent and lasting for several months following massive irradiation with a large carbon arc lamp (150 amperes and 65 volts) were reported in 1905 by Hasselbalch and Hasselbalch and Jacobaus. The pulse rate was usually not changed.

Following general body irradiation with a quartz mercury lamp in 109 observations on 19 men and 10 women Bach reports a drop in 105 averaging 7.2 mm, the greatest being 17. The pulse became stronger and more regular but did not change in rate and there was no change in body temperature.

Rosselet at Lausanne and Leysin, has always observed a fall in blood pressure during insolation with a maximal increase in pulse rate of between 30 and 40. Koenigsfeld in 92 observations on 5 persons exposed to a quartz mercury lamp found a lowering of some 2 to 8 mm immediately after irradiation which was more or less permanent. The pulse after the irradiation was usually slower, fuller and stronger, a reaction which Koenigsfeld, however, ascribes to the rest during the period of irradiation. For example: the pulse at the beginning was 76 per min., after 45 minutes irradiation it was 63, after an hour, 68. An hour's repose lowered the pulse rate to 67, the lowest figure reached in 30 minutes being 60 per minute.

Marx (1928) has recently reported the lowering of blood pressure in ambulant patients with essential hypertonia (combined with sclerosis, vascular damage, syphilis, etc.) following one hour's exposure to the energy irradiated by carbon filament lamps.

A single moderate dose of carbon arc radiation (40 g cal. per sq. cm) to the abdominal area of dogs often results in a decrease of from 5 to

20 per cent in blood pressure, persisting for about 5 hours and followed by a gradual return to normal. Repeated irradiation produces the same result day after day, the usual value being found the next morning. The pulse rate may increase during the irradiation. Body temperature shows little variation, the slight rises occurring during irradiation disappearing soon after the exposure is over. If the daily dosage be progressively increased, the magnitude of the changes is roughly proportional to the intensity of the radiation.

Marked and long lasting effects follow strong doses (83 to 124 g cal. per sq. cm) of carbon arc radiation given at intervals of 2 to 6 days. The depression thus produced is maintained for 15 to 20 days respectively at values between 12 and 22 per cent below normal.

Control dogs placed behind a screen at the same distance from the lamp while the experimental animal was being irradiated showed no changes in blood pressure, pulse rate or body temperature (Laurens and Mayerson, 1928).

The most diverse results have been reported as to the influence of radiant energy on the blood, due no doubt to the fact that the observations have been made under the most diverse conditions. The pale appearance of persons working and living in poorly lighted rooms does not necessarily mean that they are anemic; pallor alone does not mean anemia and such anemic looking people often have a surprisingly high hemoglobin content. Blood studies made during the long winter Arctic night show that, in spite of the pale, yellow-green color of the men, there is no change in the blood as long as the food is sufficient. Bernhard, sometimes called the founder of modern heliotherapy, and the great advocate of the beneficial action of sunlight on the healing of refractory wounds, is convinced, however, of the harmful effects of the lack of light as exemplified in what he calls the anemic condition of those who live on the shady side of deep Alpine valleys, as contrasted with those who dwell where they are reached by the sun's rays. He further claims that Eskimos and members of polar expeditions are, at the end of the long winter night, anemic, edematous and weak. Bernhard believes that the reason why some have not reported such conditions is that the winters were spent on an illuminated ship. Further, that the reported failure to find evidence of anemia in mine horses is due to the fact that the mines are artificially illuminated. On the other hand observations on mules kept in almost always dark mines for from 5 to 10 years show but a slight increase in red blood cells and

a corresponding decrease in hemoglobin. The increase in the reds is thought to be due to the very good and abundant diet and the hard work that the animals do, an increased metabolism, thus representing an over-compensation against any possible deleterious influence that the lack of sunlight may have.

There is evidence showing that, although the responses of red blood cells during a period of irradiation may vary, there is an eventual, greater or less, increase in the count during the post-irradiation period (Mayerson and Laurens, 1928). In some cases, especially after massive irradiations, the red cells are larger and less saturated than before, while they are small and pale during the post-irradiation period. This may be due to the fact that during the irradiation period there is a minimum formation of new cells, the system calling chiefly on its reserves, while in the post-irradiation period the bone marrow has exhausted its stores and is making new cells, low in hemoglobin and of low color index. Effects such as these have frequently been observed in conditions where there is a strong stimulus to the formation of red cells, as in regeneration from hemorrhagic anemia, the increase following emotional stress, and in severe anemia.

Blood platelets are also usually increased by irradiation, as are the whites, though many observers under the conditions of their observations have reported a decrease or no change. The increase in whites seems to be dependent on the action of a narrow range of ultraviolet wave lengths (shorter than 320 or 300 $m\mu$). The primary marked decrease in the number of the blood cells so frequently observed has recently been again demonstrated to be due to a dilution effect produced by an increase in the volume of blood plasma of beteen 6 and 37 per cent. Furthermore red cells may be destroyed by doses of radiation too large, preparations showing many cells of abnormal size and shape as well as cell fragments.

While sunlight undoubtedly benefits general health there is very little evidence that it influences specific immunity, although it is extensively believed that it increases the general resistance of the body to infection. But there are some who question this (Hill and Clark, 1927) and go so far as to say that the conclusion that ultraviolet radiation increases the resistance of animals and man to all infection is not materially supported by any experimental or clinical evidence. A number of clinicians (Mackay, 1927; Barenberg, Friedman and Green, 1926; Barenberg and Lewis, 1928) conclude that the health of infants

as indicated by the incidence of infections is but little, if at all, influenced by carbon and mercury arc radiation. Some (Bannerman, 1927; Gonce and Kassowitz, 1928) report that the mercury arc has no beneficial effect on the bactericidal property of blood but may in fact, lower it. Comparative observations indicate that following a sun bath a normal man develops and maintains a quite high hemobactericidal action, while another, whose power was considerably below the normal, went from bad to worse and did not recover the loss within 24 hours.

Irradiation influences the storage of calcium and phosphorus and the equilibrium of these elements in the blood stream of mature animals in a way similar to the effects upon growing animals. The antirachitic factor (vitamin D or radiant energy of certain wave lengths) represents specifically the organic agent which promotes normal calcium anabolism. It may cure rickets, it may promote growth or it may simply prevent excessive loss of lime from the body. The specific capacity in which it functions depends upon the condition of the animal, both with respect to age and nutrition, and upon the composition of the diet. Radiation revives a depressed function. When vitamin D is completely absent from the diet, radiation can not bring about normality in either growth or bone calcification, the degree to which they approach normality depending upon the pre-experimental store of the factor. But even when the calcium and phosphorus balance is good and the supply of each adequate, the absence of the antirachitic vitamin from the diet will result in the production of imperfectly calcified bones. The antirachitic vitamin is prepotent in preventing rickets, and is capable of doing so in the entire absence of radiant energy. At the same time ultraviolet radiation may rectify partial but not absolute lack of the dietetic components necessary for ossification. Radiant energy and vitamin D cause the organism to operate more economically.

The process of ultraviolet irradiation is regarded as giving rise to vitamin D from the bodily stores of certain sterols which find their way into animal tissues from plant sources. The animal world is dependent on the plant world for its supply of vitamins. The transference of vitamin D from vegetable source to final place of storage in the cod's liver has been traced. The cod is carnivorous and feeds on herrings, crustaceans, squids, and so on, which in turn feed on plankton. Plankton comprises minute adult and larval crustaceans, worms and so on, which nourish themselves on the minute chlorophyllaceous diatoms which abound in the surface layers of the sea. In the presence

of diffuse sunlight diatoms are capable of forming vitamins from the purely inorganic constituents of the medium in which they grow. Fresh water algae and yeasts likewise flourish under these conditions and at the same time form vitamins capable of restoring to rats, kept on a vitamin free diet, their power to grow normally.

It has been shown in this country (Hess and Anderson, 1927) and in Denmark (Sonne and Rekling, 1927) that wave lengths shorter than those of sunlight are more potent in healing rickets than the effective solar rays viz., from 290 to 313 mμ. Sonne has found wave length 253 mμ effective, the action of lines 240 and 248 mμ very slight, that of 313 mμ questionable, and of 366 nil.

The most important specific influence affecting the structure of the teeth during development is the intake of vitamin D, or the exposure of the skin to sunlight or other source of ultraviolet radiation. Vitamin D or radiation controls the actual calcifying process. Naturally, since teeth are made up so largely of calcium and phosphorus, the diet must contain sufficient of these elements.

The antirachitic factor is of great importance to the growth and reproduction of animals. Hen's eggs are especially rich in the antirachitic factor. Hens on a diet devoid of the antirachitic factor lay comparatively few eggs even during the productive period, the eggs contain very little of the antirachitic factor, fertile eggs fail to hatch, and the livers of these hens also lack this substance. Irradiation improves such conditions.

Intestinal absorption plays an outstanding role in the effects of radiation. The mechanism by which the absorption from the intestine is increased is influenced by two factors, the reaction of the gastrointestinal contents and the fat intake, as in cod liver oil. Alkalies diminish mineral absorption, while acids increase it. The absorption of calcium is initially dependent on the free acid of the gastric juice, affecting the solution of calcium salts in the diet, and is normally restricted by the alkaline reaction of the intestinal secretions which tend to neutralize and so precipitate lime as insoluble phosphate.

Deprivation of vitamin D produces in the intestinal tract a greater tendency toward alkalinity and restoration of the vitamin brings the reaction back to acid. Under normal conditions, the gastric hydrochloric acid probably is sufficient to render into soluble form practically the whole of the calcium in the food. As the food passes down the intestine the gastric acidity tends to be more or less neutralized by the

bile and other alkaline secretions and calcium may be precipitated as carbonate, as soap, or as phosphate. A phosphoric esterase in the wall of the small intestine performs an essential part in calcification in the bones by liberating phosphate ions and thus precipitating calcium phosphate. This has an optimal p_H range of 8.4 to 9.4, and rapidly loses its activity as the p_H falls from 7.5 to 6.8. Provided that this enzyme is present in the intestine, the suggestion arises that the change in fecal and intestinal reaction from alkaline (p_H 7.2 to 7.8) to acid (p_H 6.5 to 6.8) which has been shown to occur in rachitic rats after administration of an antirachitic substance (Redman, Willimott and Wokes, 1928) may, by retarding the action of the phosphoric esterase, diminish the precipitation of calcium phosphate and thus facilitate calcium absorption from the intestine (Yoder, 1927).

It has also been shown that in puppies fed a rickets producing diet the reaction of the intestinal contents tends to be more alkaline (the p_H of the small intestine varying from 6.4 to 7.4) and that the addition of cod liver oil or irradiation tends to bring the reaction back to its normal range (Grayzel and Miller, 1927). But recent attempts to obtain a definite correlation between different stages of the disease of rickets and the p_H values of the feces of children treated or not with carbon arc or mercury arc radiation have not been successful (Redman, 1928).

Infantile tetany is a condition often associated with the low calcium form of rickets. Tetany is due to the taking away of calcium from the tissues, while in rickets there is an inability on the part of the bones to bind calcium. Irradiation may lead to more marked manifestations of tetany as long as the rachitic disturbance exists and latent tetany may thus become manifest. Rachitic tetany sometimes seen at the beginning of treatment is due to a sudden demand for calcium. In florid rickets the blood calcium is practically normal and falls only when healing begins, due to the increased need during healing on the part of the bones which is met by drawing upon the calcium in the blood and other tissues. It is thus advisable to administer calcium along with the radiant energy, at first at any rate. Manifestations of spasm, tetany, and convulsions in the early spring may thus result from sudden and prolonged exposure of children to strong sunlight.

Everyone is now familiar with the fact, demonstrated in 1924 by Hess, and Steenbock and Black, that certain substances with no active antirachitic, bone forming, or growth promoting powers, may have

these bestowed upon them by irradiation. Thus diets deficient in these respects may be made complete by irradiation or by the addition to them of irradiated substances. When some animals (rats, goats, cows, chickens, men) are irradiated, their organs and body products have calcifying and growth promoting properties imparted to them. In other words, body constituents are activated. Irradiation of the nursing mother produces a protective quality which can be transmitted through the milk to the young or to other animals. Summer sunlight appears to have a small effect in determining the antirachitic value of cow's milk. Hess demonstrated the production of antirachitic human milk by the irradiation of a woman whose milk before irradiation had no antirachitic influence.

There are thus two methods by which an animal may acquire the benefits of irradiation in so far as mineral metabolism is concerned: first by being itself irradiated, and second by eating irradiated substances. Some of the things which have been activated are various oils, such as olive, linseed, cottonseed, corn, bean and peanut; cholesterol (a fat like constituent of animal cells), skin, wheat flour, milk, milk powder, chicken mash, hay, spinach, lettuce, orange juice, yeast and sawdust. Some of the things which have proven refractory to activation are chlorophyll, hemoglobin, red blood cells, cream, egg phosphatide, mineral oil, casein, agar, glycerol, fatty acids, terpenes, proteins, carbohydrates, salts, water, ether, and so on. When an animal is irradiated vitamin D arises as the result of the activation of skin sterols and is then absorbed by the blood stream.

American, British and German investigators have demonstrated that "pure" cholesterol contains an impurity or "provitamin" which is vastly more antiricketically activatable by ultraviolet rays than the preparation in which it is detected. Spectroscopic and biochemical tests have indicated that the contaminant is the trebly unsaturated (three double bonds and a hydroxyl radical) and highly unstable ergosterol, or a sterol indistinguishable therefrom, and that this constitutes less than one part per thousand of cholesterol. While cholesterol can be completely freed from provitamin by any of several procedures—treatment with charcoal or permanganate, over-irradiation, or purification via allocholesterol, cholesteryl chloride, or cholesterol dibromide—the purification of sterols is beset with difficulties and several supposedly pure sterols have been found to be persistently intimate mixtures.

Bills in 1925 reported that cod liver oil cholesterol, which, after recrystallization, had been purified by treatment with charcoal, retained the property of becoming antiricketic upon irradiation. Further, although it had been reported that cholesterol in solution loses its selective absorption on standing for several hours, that a solution 17 days old still exhibited characteristic absorption bands with no apparent diminution. In January 1928 he demonstrated that cholesterol specially treated with charcoal or bromine for removal of ergosterol was still activatable by ultraviolet rays to 1/30th the amount of the original cholesterol, whereas only 1/150th of the original ergosterol was still present, according to the absorption spectrum. This activatability (considered due either to cholesterol itself or to some hitherto undiscovered impurity) which persists after three purifications with bromine, is associated with absorption bands at 315 and 304 mμ. Others (Jendrassik and Keményffi) have also shown that highly purified cholesterol is activatable. These results have been construed as making it seem probable that the specific antirachitic substance has not yet been obtained in a pure state and that other sterols may also be activatable. On the other hand, Rosenheim and Webster (1928) are sure that ergosterol is the specific parent substance of vitamin D and that only a molecular structure such as that possessed by ergosterol enables a sterol to be photochemically converted into vitamin D.

The reliability of irradiated ergosterol has been demonstrated in the prevention as well as in the cure of rickets, being more rapid in its action than is cod liver oil or direct irradiation. Irradiated ergosterol has an antirachitic action when as little as from 0.0001 to 0.00005 mg per capita is fed to rats. The curative dose for humans is given as from 2 to 5 mg per day. Ergosterol is approximately 100,000 times as potent as cod liver oil, 5 mg being said to be equivalent to approximately 1 liter of good cod liver oil (Rosenheim and Webster). The maximum potency is developed after a few minutes (20 to 30) irradiation (using 0.1 per cent solutions of pure ergosterol in ether or alcohol enclosed in quartz tubes filled with nitrogen or evacuated) and the antirachitic activity of the reaction products remains constant up to 4 hours irradiation. It is thought that after a short initial period the formation and destruction of the vitamin probably proceed at the same rate, so that the activity remains constant till the available supply of ergosterol is exhausted.

Comparatively long waved ultraviolet radiations (296 mμ is the shortest) are capable of activating ergosterol. Human skin contains some 13 to 24 per cent of cholesterol, and Rosenheim and Webster isolated from pig's skin a typical specimen of cholesterol showing the ultraviolet absorption characteristic of ergosterol. There is, therefore no obstacle to the belief that the curative action of sunlight in human and animal rickets is due to the formation, under the influence of radiation, of vitamin D from the ergosterol in the skin. To some, the direct formation of vitamin D from ergosterol seems the most significant advance which has been made in the chemistry of vitamins since the existence of these substances was first demonstrated.

The cathode rays are also said to be able to activate substances, this having been demonstrated in the case of cholesterol, yeast, starch and cotton seed oil. The claim is made that yeast is rendered very potent by such exposure (Knudson, 1927).

It is believed by some that the effective antirachitic principle may arise without the action of ultraviolet radiation. Grasses were grown under different conditions excluding ultraviolet rays and then fed to rabbits made experimentally rachitic. It was found that grass seeds do not contain the antirachitic factor and that when the seeds germinate, the factor appears even if the grass has grown in complete darkness. Grass grown on a synthetic medium in absolute darkness to a height of 10 to 12 centimeters has also been claimed to heal rickets, but somewhat less so owing to the low concentration of salts. Vitamin A is formed in plants grown in darkness.

Reported results on the action of radiant energy on basal metabolism are contradictory. Kestner and his co-workers show that irradiation leads to an increase in oxygen consumption. Other investigators believe that the increase, when observed, as on exposing the nude body to sunlight on the seashore or on a mountain, is due to the increased cooling. To obtain this metabolic increase (the aim of all climatotherapy) the velocity of the wind and the heat from the sun's rays should be moderate. When the wind is of low velocity and the heat from the sun's rays is great, the basal metabolism is lowered on account of the coming into action of the chemical heat regulating mechanism.

Ordinary window glass is impervious to the rays of sunshine shorter than about 320 to 330 mμ and much effort has been devoted of late by glass manufacturers to the production of glasses that will transmit some of the shorter ultraviolet rays. In the interests of reality there are some

things that should be emphasized. Aside from the fact that some of these glasses do not transmit, qualitatively or quantitatively, very much more ultraviolet than ordinary window glass, the transmission of nearly all of them is much decreased after several hours exposure to sunlight and artificially produced radiant energy. Everyone is familiar with this work of the Bureau of Standards.

As you all know these glasses have been much advertised for use in hospitals, nurseries, schools; in situations where during the winter although the sun may be shining it would be uncomfortable, inconvenient or impractical to expose the nude, or partially clothed or even fully clothed body to the sunshine of the open air. In the first place there is in winter sunshine precious little of the wave lengths of ultraviolet which these various glasses transmit in contrast to window glass. Not until late March or early April are these wave lengths present in any considerable amount. Again as Janet Howell Clark (1928) has shown, with a method that determines the intensity of wave lengths shorter than 350 mμ with maximum sensitivity at 310 mμ, in March in a north room equipped with ultraviolet transmitting windows, a child would have to sit in a place where the illumination is 10 foot candles for at least 20 hours to get as much ultraviolet radiation as he would get in 20 minutes outdoors in sunlight at noon. During March, April and May 1928 it was shown that although the intensity of ultraviolet radiation increased from March to May, it would have been necessary to sit about 15 hours at 5 meters from a north window of ultraviolet transmitting glass to get as much ultraviolet radiation as could be gotten in 2 minutes outdoors in direct sun at noon, although the illumination at this point had risen to 20 foot candles. This amount is obviously too small to be of any great value. Any child going out for recess, or any stenographer going out to lunch, will get more ultraviolet radiation than she could get all day behind a window of ultraviolet transmitting glass. So, although these materials have an undoubted field of usefulness in solaria, and probably in greenhouses, in animal houses and in zoos, it is unnecessary to put them in schools and offices where it would be cheaper and more efficient to send the individuals concerned out into the sunshine for a few minutes every day at noon. A worker finds it practically impossible to sit in the sunlight received through glass on account of the glare.

W. H. Eddy has also recently shown that these glasses do permit the ultraviolet rays of sunshine to pass into the room but they do

not go far enough or in sufficient intensity to take the place of outdoor sunshine.

The question as to just what part of the spectrum is most effective is by no means settled. If it is certain wave lengths shorter than 313 mμ which are most effective in treating and preventing rickets, is it these same wave lengths which are most effective in producing inflammation and pigmentation in the skin, in increasing the number of red blood cells and the percentage of hemoglobin in secondary anemias, in the treatment of extrapulmonary tuberculosis, in slaying bacteria and so on? Some think so, others do not. Sheard and Higgins (1928) have recently published evidence that the normal growth and mineral metabolism of chicks are dependent upon portions of the *entire* solar spectrum. These investigators go so far as to say that, as far as they know, there is no evidence to prove that ultraviolet energy of a given wave length is capable, in and of itself, of preventing rickets or nutritional deficiencies.

The effects of radiation for which we have explanations, based particularly on analogy with non-living substances, are either physicochemical or chemical in nature. Between the two there are many phenomena explicable on the basis of a shift from one or the other of these two points of view. The therapeutic action of radiation is regarded by some as being due to the speeding up of processes by the heat produced locally when the radiation is absorbed with no harmful raising of body temperature. Another view is that the various effects are due to the transport by the blood stream to various parts of the body of the chemical products formed in the skin. Cellular degeneration is a frequent sequel to irradiation of tissues and the excessive action of radiation may flood the body with too much of the products of tissue damage. Radiation may act as an oxidizing and reducing agent with the complex chemical compounds in the living cell, the molecules thus showing altered chemical reactions. The pathological action of radiation probably consists in the knocking down of the entire arrangement of the electrons so that their proteins attain an isoelectric state and coagulate.

The Journal of the American Medical Association for January 14, 1928 calls attention to the dangers of ultraviolet rays. The tendency of therapeutic methods to be adopted and discarded in great waves of popularity and forgetfulness has never been so manifested as in the current attention given to the use of the "ultraviolet ray." Prospective

victims of baldness are swindled with purple incandescent lamps. Many so-called ultraviolet ray devices deliver little or none. On the other hand, regardless of the fact that practically every method in medicine that may do good can also do harm, lamps which do emit large quantities of ultraviolet are being sold to bath institutes, swimming pools, massage and beauty parlors, clubs, barber shops and so on, in which medical supervision is probably not thought of. The sales are made notwithstanding the fact that the rays possess dangerous effects for the eyes, that some people who do not tan easily are potentially poor subjects, that persons with fever tend to do extremely poorly under the use of the rays, that persons with low blood pressure react sometimes with serious symptoms, that persons with early tuberculous conditions may be greatly harmed, that menstruation in women constitutes a contraindication to the use of ultraviolet rays, and that there are innumerable records of severe skin injury following over-exposure to ultraviolet rays in persons who are over sensitive. Moreover, the rays are being advised as useful in a vast number of conditions for which the scientific evidence is extremely slim.

Scientific medicine knows no panaceas, no therapia magna. Radiant energy is merely an adjuvant, an auxiliary to other treatment such as rest, fresh air, hygiene, diet, happy surroundings. Sunlight or artificial radiant energy will not cure, is not a specific form of treatment, and should not be used without medical guidance and adequate equipment. When it is used without regard to these truths it may dishearten the users (and many have been disheartened) and bring discredit upon an otherwise desirable method of treatment. Further, although radiation may have marked effects on abnormal conditions, it plays only a minor part in the daily life of normal persons who can get along with little or no sunlight provided the diet is adequate.

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SOME EFFECTS OF RADIANT ENERGY ON PLANTS

By John M. Arthur

The plant grows under natural conditions because it has adapted itself to grow there. This is an axiom which is always driven home to the mind of any one who undertakes a study of the effects of environmental conditions on green plants. The ranges of quality, intensity, and duration of solar radiation are apparently well suited to the growth of plants. Knowing of the variations of quality, and especially of the extreme variations of intensity from minute to minute, day to day, and season to season of solar radiation one might conclude that plants are insensible to most of these fluctuations. One might even conclude that the plant will grow in about any quality and intensity of radiation.

Only by exceeding the limits of intensity, quality, and duration ranges of solar radiation can one be convinced that after all the plant is not only not indifferent to these changes but is attuned to some of them and is easily injured whenever the natural range is greatly exceeded in any direction. An increase in total intensity by a few per cent beyond the maximum for solar radiation results in injury. Any great increase in day length results in injury to some plants, and certainly any great extension of the range of wave lengths included in the extreme ultraviolet component of the solar spectrum will result in injury. On the other hand if any considerable region is taken away from sunlight very definite effects can be observed on growing plants. If the blue or red region is absorbed from the solar spectrum the resulting radiation produces very characteristic effects upon plants.

Carbon fixation by green plants, or photosynthesis as physiologists have been pleased to call the process, goes on in the red and blue regions of the visible spectrum. It also goes on in the ultraviolet region as observed by Ursprung[1] and Wurmser,[2] but is not known to occur in the infrared. The amount of photosynthesis which goes on in the ultraviolet is probably small. The energy relation of the process is one

[1] Ursprung, A. Über die Stärkebildung im Spektrum. Ber. d. d. Bot. gesell., *35*, pp. 44–69; 1917.

[2] Wurmser, R. L'action des radiations de differentes longueurs d'onde sur l'assimilation chlorophyllienne. Compt. Rend. Acad. d. Sci., *171*, pp. 820–822; 1920.

of the classical exceptions to Einstein's photochemical equivalence law as observed by Warburg[3] and associates, since they found that 4 energy quanta are required in the red and yellow and 5 in the blue per molecule of carbon dioxide dissociated in the process of photosynthesis. These observations were made upon green algal filaments, for very short time intervals and using monochromatic light. As already pointed out seed plants will not grow well when a single region such as red or blue is removed from the visible spectrum. We certainly would not expect therefore to grow plants during their life history with monochromatic light. Not only energy is required for the life processes of plants, but a certain distribution of energy at various wave lengths in the visible region is required as well.

Since the discovery was made that the extreme region of the solar spectrum between wave lengths 313 and 290 mμ would protect animals from rickets, biochemists have looked for a comparable effect in plants. When grown in the open sunlight in summer, plants have normally an increased amount of many organic and inorganic constituents as compared to similar plants grown under glass during the winter. This may be due to an increase in light intensity, increase in the ultra violet component, increase in air movement, or to other factors. It may be due to a combination of two or more of them. Tottingham and Lowsma (5) have recently observed that corn plants show increased absorption of nitrate and an increase in protein synthesis when exposed directly to sunlight during the late summer as compared to plants similarly exposed under glass. This may be accounted for by the difference in light intensity as well as quality under glass as compared to outdoor conditions, since their own work shows that lower light intensity causes marked decrease in nitrate absorption. To date we have no definite proof that seed plants absorb more minerals as a result of exposure to the extreme ultraviolet of sunlight, or that these plants are definitely benefited in any way by exposure to these rays.

Several studies have been made at the Boyce Thompson Institute upon plants grown in 5 different houses, each of which is covered with a glass filter which absorbs a definite region of the solar spectrum. The transmissions of the glasses are as follows:

1. Visible region and to wave length 313 mμ in the ultraviolet.
2. Visible region and 80 per cent of the incident radiation at wave length 290 mμ in the ultraviolet.

[3] Warburg, Otto. Versuche über Kohlensäure assimilation. Die Naturwissenschaften, *13*, pp. 985–993; 1925.

3. Visible region except red from wave length 585 mμ to 384 mμ.
4. Visible region from wave length 720 mμ to 472 mμ.
5. Visible region except blue from wave length 720 mμ to 529 mμ.

The results of these studies have shown that there is no marked difference in the form, dry weight, or time and amount of flowering whether the plant receives the extreme ultraviolet of sunlight as in house 2 or receives only that portion of it transmitted by window glass (house 1). No marked differences were found in the carbohydrate and nitrogen fractions in the two series. When plants are grown without the blue region (house 5) there is a marked difference. The stems are

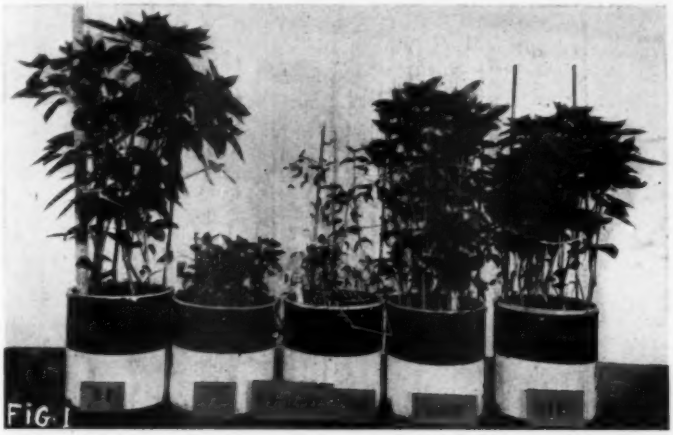

FIG. 1. *Four o'clock grown in spectral houses 2, 3, and 5. The "shade" plant was grown outdoors under shading cloth at an intensity slightly higher than house 5. Roof plants were grown in open sunlight. House 2 transmits the visible and ultraviolet regions, house 3 glass transmits no red, and house 5 glass transmits no blue.*

thin and weak and the leaves are small, and there is a tendency to roll downward from the midrib toward the margin. These plants appear as though they were grown in deep shade. When plants are grown without the red (house 3) they have a normal appearance but probably on account of the low intensity under this glass they do not grow to normal height. Further experiments are now in progress to determine whether by increasing the solar intensity under this filter a plant can be grown which has the same height and weight as under the complete solar spectrum of equal intensity. An increase in the total intensity under the red filter (house 5) would probably make very little difference

in growth since this intensity is already comparatively high. The total intensity in house 5 is about 37 per cent of outdoor conditions as compared to 11 per cent in house 3. Two species of plants grown with the different regions of the solar spectrum are shown in Figs. 1 and 2.

Most plants can be grown with artificial light. The gas filled incandescent filament lamp has been used at the Institute, both as the sole source of energy and to supplement sunlight for 6 to 12 hours each night. In the first case 25, 1500-watt lamps were used in a room approximately 11 feet square. A glass-water filter was placed between this

FIG. 2. *Petunias grown in spectral houses 2, 3, and 5. This shows the effect of growing a plant without the blue region (house 5) and without red (house 3).*

light source and the growing plants to remove some of the infra red. Temperature and humidity were accurately controlled by cooling and recirculating the air by means of standard air conditioning machinery. In the second series of experiments a gantry crane carrying 48, 1000-watt lamps was used. This crane was moved into place over the greenhouse and served as a source of illumination for a few hours each night (Fig. 3). In both series of experiments additional carbon dioxide was supplied to the plants. The normal concentration of this gas in air often limits plant growth when light intensity is high. Air temperature was kept relatively high in some experiments (78° F) in order to

FIG. 3. *Gantry crane used to supplement daylight. This crane carries 48, 1000-watt lamps.*

FIG. 4. *A series of tomatoes grown on daylengths varying from 5 to 24 hours of artificial illumination. This shows the injury of continuous illumination (24 hour day) upon this species.*

determine how far the rate of photosynthesis, and consequently growth, could be increased. Here, as in most extremes of radiation a limit is easily reached. Some plants, such as the tomato, will not withstand continuous illumination. A leaf injury appears in about five days under continuous exposure and gradually increases until most of the leaves have withered and dropped off of the plant. A series of tomato plants grown in the light room on various day lengths from 5 to 24 hours are shown in Fig. 4. The control plant was grown in a greenhouse with normal solar radiation and at the same temperature. The extreme injury of continuous illumination (24 hour day) is also shown. In general, an 18 to 19 hour day gives about as much growth and weight

FIG. 5. *Lettuce, a long day plant showing the flowering initiated by a daylength greater than 12 hours and the tendency to form a head on short days of 12 hours or less.*

increase as a 24 hour day. The effects of day length on flowering as observed by Garner and Allard (3) apply here. Plants such as lettuce and raddish which flower on the long days of summer, flower on day lengths greater than 12 hours. This is illustrated by a series of lettuce plants grown with various day lengths from 5 to 24 hours, shown in Fig. 5. Short day plants which normally flower in the spring or fall, flower on 15 hours or less exposure to artificial illumination. Fig. 6 illustrates a series of salvia plants which shows the effect of day lengths in initiating flowering in a typical short day plant. Only an occasional flower will be produced on a 17 hour day while this type flowers well

on a 12 hour day. Another group such as the buckwheat flowers on all day lengths from 5 to 24 hours. The effect of day length on this species is shown in Fig. 7.

FIG. 6. *Salvia, a short day plant. This plant flowers on a daylength of 15 hours or less. An occasional terminal flower is produced on a 17 hour day.*

Siemens in 1880[4] observed that the radiation from a carbon arc was injurious to plants. Melon and cucumber leaves, when exposed

FIG. 7. *Buckwheat, an "everblooming" type. This plant flowers on all daylengths from 5 hours to 24 hours. The control plant was grown in the greenhouse at the same temperatures during the month of March.*

at a distance of 1 meter or less, rolled up at the edges and assumed a

[4] Siemens, C. W. On the influence of light upon vegetation and on certain physical principles involved. Proc. Roy. Soc., *30*, pp. 210–219; 1880.

scorched appearance. He avoided this difficulty by placing the plants farther away from the lamp. Many workers since that time have observed that this injury is caused by the ultraviolet component of such radiation which is absorbed by window glass. Light sources which emit this region of the ultraviolet such as the mercury vapor arc in quartz and the iron and carbon arcs in general produce severe injury to plant tissue when exposed without a filter. Solar radiation has also been observed to injure foliage of plants when the atmosphere is unusually clear in mountainous regions. Plants growing under glass in such conditions are thought to be protected. As pointed out above this protection may be due to a decrease in total intensity brought about by the greenhouse roof as well as to the absorption of the extreme ultra violet region.

A series of experiments has been carried on recently at the Institute to determine approximately the region, in the ultraviolet component of a mercury arc in quartz, which is injurious to plants, and further, the relation between the region transmitted by various filters and the time necessary to produce injury on young tomato plants. Plants were exposed at a distance of approximately 15 inches from the quartz tube to the tip of the plant, and through an opening 6 inches square in the metal shield around the lamp. The unprotected arc and five filters, which absorb ever increasing portions of the region between wave length 185 mμ to 300 mμ, were used in the study. The transmissions of the filters were approximately as follows:

1. G970C—1.9 mm thick—limit of transmission 237 mμ—1% @ 249.7 mμ
2. G970C—3.11 mm thick—limit of transmission 237 mμ—1% @ 249.7 mμ
3. G970A—3.99 mm thick—limit of transmission 253 mμ—1% @ 273.7 mμ
4. S 1—2.00 mm thick—limit of transmission 270 mμ—1% @ 281.1 mμ
5. S 1—5.06 mm thick—limit of transmission 286 mμ—1% @ 293.5 mμ

When young tomato plants are exposed to the open arc as outlined above, severe injury and a killing back of a great part of the leaf area is produced in 30 seconds. The effect of irradiating tomato plants for 30, 60, and 120 seconds respectively, each day or every second day,

[8] Tottingham, W. E. and Henry Lowsma. Effects of light upon nitrate assimilation in wheat. Jour. Amer. Chem. Soc., *50*, pp. 2436–2445· 1928.

over a 17 day period is shown in Fig. 8. Filter 1 will produce a similar injury but not as severe, in about 15 minutes exposure. Filter 2 produces a similar injury in about an hour. It requires three hours to produce as much injury with filter 3, and 12 hours with filter 4. Young tomato plants which have received 7 exposures in a 10 day period of 2 and 3 hours respectively through filter 3 are shown in

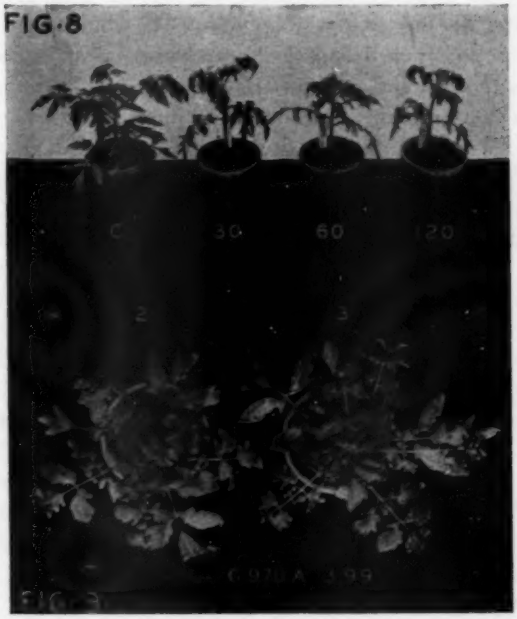

FIG. 8. *The injury to tissue produced by short exposure to the quartz mercury vapor arc without a filter. Left to right, the control plant, and plants exposed for 30, 60, and 120 seconds respectively, each day or every second day over a 17 day period.*

FIG. 9. *Tomato plants irradiated through filter No. 3 for 2 and 3 hours respectively, each plant received 7 exposures in a 10 day period. When the exposures did not exceed 2 hours the plant was almost completely protected while 3 hours exposure produced severe injury.*

Fig. 9. The plant exposed for only 2 hours was almost completely protected while the one exposed for 3 hours was definitely injured. With a quartz plano-convex lens 4 1/2 inches in diameter and 8 1/2 inches focus mounted over the face of filter 4 an equal injury can be produced in about 3 1/2 hours. Pyrheliometer measurements have shown the total energy without the lens to be about .14 gram calories

per square centimeter per minute as compared to .42 gram calories with the lens. This indicates that the effect produced is approximately proportional to the incident radiant energy at the same wave lengths and that the intensity of the effect, or rate of killing, increases rapidly with decreasing wave length. If we assume the killing effect per unit of time from the open arc equal to 1, it takes approximately 30 units to produce the same effect through filter 2, as compared with 360 through filter 3, and 1440 through filter 4, while filter 5 protects indefinitely. So far no injury has been observed after prolonged irradiation both with and without the lens through filter 5. Coblentz and Kahler[2] have shown that the total amount of ultraviolet radiation from a similar quartz mercury arc of wave length less than 400 mμ is about the same for solar radiation and for the mercury arc, that is about .02 gram calories per square centimeter per minute. The energy distribution they point out further is very different, since sunlight terminates at about 300 mμ at near sea level while the mercury arc has 5 per cent of its total radiation, or 20 per cent of the ultraviolet component, of wave length shorter than 300 mμ. This being the case, since no injury is produced by energy transmitted through filter 5 even though it is concentrated threefold, it is thought that no injurious rays can exist in the ultraviolet component of solar radiation at altitudes where plants grow. This filter transmits to wave length 285 mμ and transmits 1 per cent at 293.5 mμ. Since the limit for solar radiation is wave length 290 mμ and the energy at this wave length must always be extremely small it is believed that it could not cause injury to plant tissues.

In conclusion it should be pointed out that the limit of the energy range for plant growth is definite in the ultra violet region, and that one needs to overstep the limit of solar radiation as the plant ordinarily receives it by an extremely narrow margin to cause marked injury to tissues. It has been observed by Bovie[1] that this injury not only continues into the Schumann region but increases with decreasing wave length. Other workers have shown that shorter rays, the x-rays, cause

[1] Bovie, W. T. Effect of the Schumann region on plants. Bot. Gaz., *61*, p. 1; 1916.

[2] Coblentz, W. W. and H. Kahler. A new spectrophyrheliometer and measurements of the component radiations from the sun and from a quartz mercury vapor lamp. Sci. Paper Bur. Standards No. 378, 1920.

[3] Garner, W. W. and H. A. Allard. Effect of relative length of day and night and other factors of the environment on growth and reproduction in plants. Jour. Agr. Res., *18*, p. 553; 1920.

definite reactions in plants where they are absorbed. Most of these regions, where absorbed by plant tissue, result in definite injury which may or may not lead to stimulation of growth or even possible change in genetic constitution. So far as our observations go in the ultraviolet region there is no marked stimulation but only injury. Much more work needs to be done before we can be sure of this, since the evidence is negative and probably not all known methods of determining stimulation have as yet been used.

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THE NATURE OF THE SENSITIVITY OF ANIMALS TO LIGHT*

By Selig Hecht

I. GENERAL PROPERTIES

Almost all animals are sensitive to light. A significant thing about this sensitivity, however, is not merely its wide-spread occurrence, but the similarity of its manifestations in different animals. There seem to be certain general properties which are common to nearly all light sensitive animals. This would indicate that there is a basic similarity in the organization of the sensory system; that the relation between light and its reception by animals partakes of a pattern which is determined on the one hand by the properties of light and on the other by those of the nature of animals. It is with this fundamental similarity and with the nature of the processes underlying it, that the present paper is concerned.

Let us consider briefly some of these common properties of the photosensory system. The most obvious one is the capacity of animals to adapt themselves to light. For instance, after we have been in the dark for several hours, even a comparatively weak illumination represents a strong stimulus, as the common experience of turning on a light in the middle of the night bears witness. In a short time however the eye becomes accustomed to this illumination and is no longer bothered by it. We move on the street in broad daylight surrounded by illuminations several thousand times more intense than the weak light which annoys us when it is suddenly turned on in the dark. A similar thing is true of other animals. Take for example the light sensitive clam, *Mya*. If after being kept in the dark it is illuminated suddenly, it responds to this illumination by a vigorous contraction of its siphons. If the illumination, no matter how powerful it may be, is permitted to continue the animal no longer responds to it. Closer study of photo-

* This paper was presented at a joint meeting of the Philosophical Society of Washington and the Biological Society of Washington in conjunction with the Michelson Meeting of the Optical Society of America on November 3, 1928. It was illustrated with many lantern slides, of which only a few are reproduced in the present paper. All of the curves and figures here reproduced are taken from the Journal of General Physiology, where most of the original data have been published.

intensity is the threshold. Below this threshold the light may be on indefinitely but we do not see it. The threshold for light varies among animals, and in the same animal under different conditions of light and dark adaptation. But under constant conditions, it is constant.

These five properties, namely, light adaptation, dark adaptation, intensity discrimination, the dual nature of the receptor process, and the existence of a threshold are not the only properties of the visual process common to most animals. They are merely those general properties which are familiar because of everyday experience. Detailed

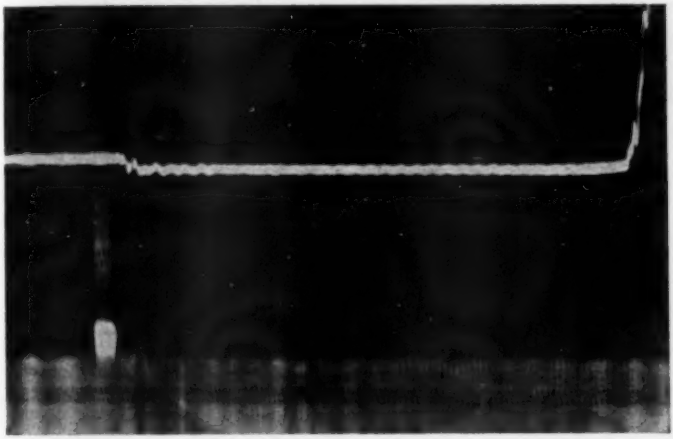

FIG. 1. *Optical records of the stimulation of the clam, Mya arenaria, by a short flash of light, and its response after a long latent period. The white streak running the length of the figure represents the movement of a mirror attached to the tip of the light sensitive siphon of the animal; the contraction of the siphon is registered by the vigorous upward movement of the line. The white spot and dim vertical streak at the left give the duration of the exposure (0.07 sec.). The siphon responds nearly two seconds after the exposure. The slight irregularity in the siphon record immediately after the exposure is due to an accidental vibration of the mirror caused by the movement of the shutter. The tuning fork marks 50 vibrations per second.*

studies of the quantitative relations involved in them have brought out not only their own exact nature, but have discovered to us properties of the photosensory system the existence of which were never suspected, and which in turn have helped to elucidate the nature of the process.

II. EXPOSURE PERIOD AND DARK ADAPTATION

Since it is obviously impossible to describe the details of all these experiments, one may choose to illustrate this development by a con-

sensitive animals shows that after light adaptation they become less sensitive to light. This essentially constitutes light adaptation.

A second and certainly as significant a characteristic of light sensitive animals as their light adaptation, is their capacity for dark adaptation. Animals which have come into sensory equilibrium with their light environments and which in consequence have lost much of their sensitivity to light, will regain their sensitivity if they are removed from the light and kept in the dark. The change from light to dark adaptation and from dark to light adaptation goes on all the time in our own lives and may be reversed experimentally an indefinite number of times. Most of us who pay any attention to our sensations are aware of the changes associated with these two properties,—with light and dark adaptation,—though their full magnitude and their regularities become apparent only on closer investigation.

A third property which is not so obvious unless attention is called to it, is the capacity for intensity discrimination. Animals must evaluate their environment, and have developed organs of special sense for doing this. The light environment of animals varies in intensity and in composition. Some animals have built organs which are specially concerned with evaluating the composition of light; this is color vision, and is a comparatively restricted capacity. But, practically all animals can discriminate intensity. It is undoubtedly one of the most useful things which the light sense accomplishes, because the recognition of the form and presence of objects rests on differences in intensity.

There is a fourth property of the visual mechanism which also becomes familiar after it has been pointed out. This is the curious fact that we see a light only after it has been on for some time, and continue to see it after it has been turned off. In the case of the human eye, the period during which the light must be on, and the period during which it may be off are very short and require special devices for their demonstration. Nevertheless, the cinematograph bears witness to their existence. However there are animals in which these two parts of light reception are clearly marked, and sufficiently long for simple demonstration. They have therefore become well-defined entities possessing other distinguishing features, as will presently become apparent.

A fifth property of the photoreceptor system concerns the matter of the threshold. Apparently it requires a certain intensity before an animal can see, or before an animal can respond to light. This minimal

sideration of just three of the properties already enumerated. The first will be the double nature of the sensory process; the second, the course of dark adaptation; the third, intensity discrimination. The first two will be treated rather sketchily; the third in some detail.

As we saw, the time from the moment a light is turned on to the moment we stop seeing it after it has been turned off is not a simple interval, but is composed of at least two parts. This may be demonstrated very simply with animals like the clam *Mya* and the ascidian *Ciona*. The period during which the necessary amount of energy is

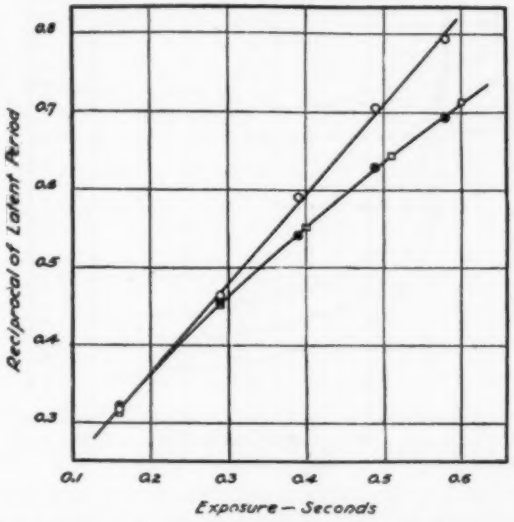

FIG. 2. *Relation between the duration of the exposure to light and the reciprocal of the latent period. The connection between the two is practically linear, being exactly so in one experiment, and very nearly so for the two other experiments shown in the figure.*

received may be about 0.1 second or shorter. The period in the dark which follows this before the light becomes effective as a stimulus to the nerve is 2 seconds, and may often be much more (Fig. 1).

There is a definite connection between these two parts of the stimulation period, in that the secondary part (the "dark," latent period) varies inversely with the duration of the primary (or exposure) period. If one takes a given intensity of light, and subjects an animal to a series of exposures varying in duration, and then measures the duration of

the latent period before the animal responds to the light, one finds an almost linear relation between light exposure and the reciprocal of the latent period (Fig. 2). Also, if the exposure period is kept small and constant, and the intensity of the light is varied, it is found that the reciprocal of the latent period varies directly with the logarithm of the intensity. Moreover if one so arranges matters that both time and intensity are varied the expected result appears, namely that the dark or latent period varies inversely as the product of the time and the logarithm of the intensity.[1]

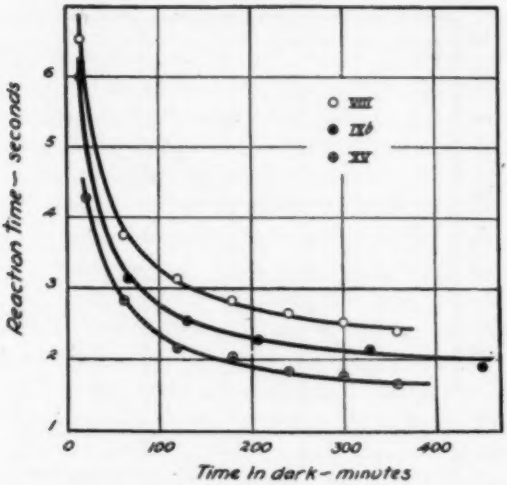

FIG. 3. *The course of dark adaptation in the ascidian, Ciona intestinalis. The three curves represent different experiments. The points for experiment XV have been lowered 0.5 second in the drawing in order to keep them distinct from the others. The curves are all rectangular hyperbolas and show that the data are adequately expressed when the course of dark adaptation is considered to follow the kinetics of a bimolecular reaction.*

These experiments can be performed with *Mya* and *Ciona* using a stopwatch and a photographic shutter. That the relationships hold when the periods of time require more elaborate methods for control and measurement has been demonstrated recently by Adrian[2] with

[1] Hecht, S., Time and Intensity in Photosensory stimulation, J. Gen. Physiol., *3*, p. 367; 1920–21.

[2] Adrian, E. D., and Matthews, R., The action of light on the eye. Part II. The processes involved in Retinal Excitation, J. Physiol., *64*, p. 279; 1927.

the vertebrate eye. The dual nature of the time interval involved in light reception is thus a general phenomenon whose properties are the manifestations of the structure and composition of the photosensory system.

The second property to be presented in slight detail is dark adaptation. The increase in sensibility of the eye is of course familiar. That the same thing is true of other animals is of comparatively recent

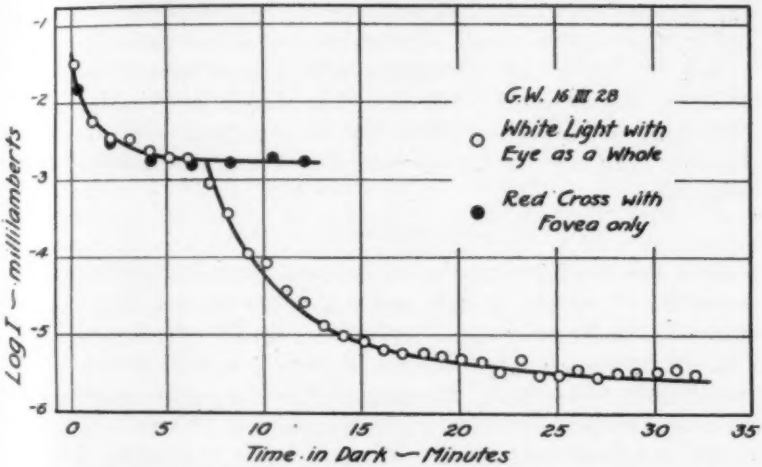

FIG. 4. *The dark adaptation of the human eye. The points are single measurements of the just perceptible intensity at different times in the dark after high light adaptation. The white circles are for white light. The black circles are for the extreme red of the spectrum which stimulates the cones alone. Dark adaptation is thus in two stages; first, cone adaptation; and second, rod adaptation. The curves are both rectangular hyperbolas and show that dark adaptation follows the course of a bimolecular chemical reaction. The data are from experiments made in our laboratory by Charles Haig and George Wald.*

knowledge.[3] After a half hour's stay in the dark the eye increases ten and a hundred thousand times in sensitivity. The course of this change is surprisingly regular. If it is followed in such animals as *Mya*, *Pholas*, *Ciona*, and the frog tadpole, the data show a uniform type of behavior. The reaction time to light, measuring the necessary amount of light for a response, when plotted against time in the dark forms a rectangular hyperbola (Fig. 3). If it be assumed that reaction time in some way measures the concentration of sensitive material present in the sensory

[3] Hecht, S., The kinetics of dark adaptation, J. Gen. Physiol., *10*, p. 781; 1926–27.

system, then these curves describe the kinetics of a bimolecular chemical reaction. It is as if dark adaptation represented the accumulation of a sensitive material formed by the reaction of two other substances.

It is surprising how adequately the kinetics of a bimolecular reaction describes the dark adaptation of quite a variety of animals from the clam to the human eye. The human eye is particularly interesting because it is a double sensory system composed of two sets of receptors, rods for dim vision, and cones for bright vision involving color. These two systems work quite independently in dark adaptation (Fig. 4), and in other respects as well. The behavior of the rods and of the cones in dark adaptation may be studied separately under special conditions, and they may be studied together. The kinetics are bimolecular in both cases, provided one assumes that the logarithm of the threshold intensity is an index of the concentration of sensitive material in the sense cell.

III. PHOTOCHEMICAL SYSTEM

Even this hasty presentation of the most general properties of the sensitivity of animals to light makes it apparent that they are the expression of the mechanism concerned with the reception of light. Can one invent a system which would produce such properties? It is several years now since we first suggested[4] such a system of processes; since then we have investigated the photosensory process in terms of it, and as a result have changed it in one respect or another. The essentials are however the same, and the system is here presented in a diagrammatic form.

$$\xrightarrow{\text{light}} \boxed{S \underset{\text{"dark"}}{\overset{\text{light}}{\rightleftharpoons}} P+A \begin{matrix} +B \\ +C \end{matrix} ; \; L \| P+A \| \rightarrow T} \xrightarrow{\text{impulse}}$$

Light enters the sensory cell. It changes a sensitive material S, present in the cell, into one or more decomposition products P, A, etc. These products of decomposition are themselves not capable of producing an impulse to the attached nerve. What they do is to catalyze a reaction $L \rightarrow T$ which is all ready to proceed but which cannot go

[4] Hecht, S., The nature of the latent period in the photic sensitivity of *Mya arenaria*, J. Gen. Physiol., *1*, p. 657; 1918–19.

without a catalyst. The substance L is a neutral, indifferent material; its product T is an active substance whose presence in a certain concentration acts to discharge the cell chemically or electrically, and to send an impulse to the attached nerve fiber. This system is simply a coupled photochemical reaction composed of a primary photochemical reaction and a secondary "dark" reaction. In addition the primary reaction is reversible as indicated in the diagram. It should be emphasized that the spatial separation of the two halves of the process is purely diagrammatic. Actually the substances are intimately mixed in the cell.

Consider now how the several characteristics of vision are derived in terms of this hypothetical sensory mechanism. Light adaptation depends on the formation of a stationary state in the reversible primary photochemical half of the system. Certain equations may be derived which show the exact relation between the intensity of the illumination and the concentration of the substances at the stationary state. These we shall see adequately describe various aspects of light adaptation.

Dark adaptation follows the course of the "dark" recovery reaction in the primary reaction, and its kinetics determine the kinetics of adaptation. The duality of the time interval associated with light reception is reflected in the two parts of the coupled reaction. The primary photochemical reaction concerns the actual exposure period to light. The secondary latent period is the manifestation of the secondary dark reaction, which in the case of many animals takes a longer time than the light reaction. Similarly the threshold represents the necessary amount of material which must be decomposed by the primary reaction to influence the secondary. Because the primary reaction is reversible only lights above a given intensity can produce this minimal amount of decomposition at the stationary state. The final property, intensity discrimination, I shall take up in much greater detail presently, and will therefore omit it for the moment.

This hypothetical model must not be taken too seriously. It is purposely kept simple because in this form it is easier to subject to mathematical treatment. The simpler a model is the more obvious are its deviations from reality; whereas computations based on a complicated model obscure their deficiencies by the closeness with which they may be made to fit the data by the use of many constants.

IV. EFFECT OF TEMPERATURE

Taking this model as a basis for the photosensory system, it is possible

to deduce certain properties which the photosensory system should show. In the last eleven years a number of such tests have been devised. As an example of such tests, I shall take one type of investigation and show how the deductions were investigated and verified. Consider, therefore, the effect of temperature on the photosensory process as it is to be expected from this hypothetical system of reactions.

There are three places in this system where the effects of temperature may be anticipated. One is the photochemical decomposition $S \rightarrow P+A$; another is the reverse dark reaction $S \leftarrow P+A$; the third is the latent period process $L \rightarrow T$. It has been known for years that photochemical reactions as such show almost no effect of temperature.[5]

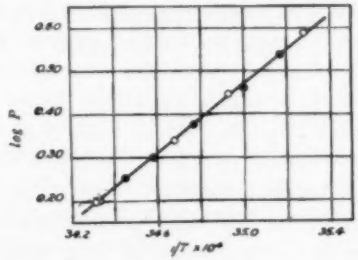

FIG. 5. *Relation between the absolute temperature (T) and the latent period (p). The open circles represent measurements taken as the temperature was decreased; the solid circles, as the temperature was increased. The equation of the straight line is $\ln p = 18{,}300/RT - 30.95$. The fact that the line is straight shows that the effect of temperature on the latent period follows the Arrhenius equation. R here is the gas constant.*

The reaction $S \rightarrow P+A$ should therefore be uninfluenced by temperature. This means that the exposure period in the visual process should vary neither in time nor in intensity at different temperatures. This obviously can be investigated only in cold blooded animals; and where it has been measured, as in the clam, it has been found that the exposure period is indeed independent of temperature.[6]

This, however, is not the case with the second part of the process, namely the latent period. The reaction $L \rightarrow T$ is an ordinary chemical reaction. Its velocity should therefore be definitely influenced by the

[5] Goldberg, E., Beitrag zur Kinetik photochemischer Reaktionen. Die Oxydation von Chinin durch Chromasäure, Z. f. phys. Chemie, *41*, p. 1; 1902.

[6] Hecht, S., The Photochemical nature of the photosensory process, J. Gen. Physiol., *2*, p. 229; 1919–20.

temperature in a manner comparable to other chemical reactions. Experiments on a variety of animals have shown this to be true. The latent period varies inversely as the temperature (Fig. 5) in such a way that its velocity is an exponential function of the absolute temperature according to the classical Arrhenius equation.[7]

Finally one may consider the effect of temperature on the recovery reaction $S \leftarrow P + A$, which is responsible for dark adaptation. This also is an ordinary chemical reaction, uninfluenced by light, and its velocity should therefore vary with the temperature. Experiments with *Mya* (Fig. 6) have shown that the velocity constant of the bimolecular

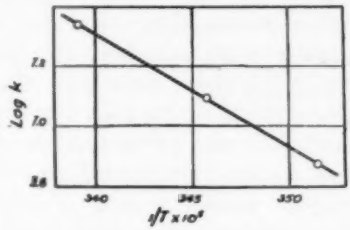

FIG. 6. *Relation between the absolute temperature (T) and the velocity constant (k) of the dark adaptation reaction. The straight line represents the Arrhenius equation and shows that the effect of temperature on dark adaptation is the same as it is on ordinary chemical reactions.*

reaction describing dark adaptation is a strict exponential function of the absolute temperature, and thus behaves exactly as other chemical reactions.[8]

These examples of the application of the hypothesis are enough to indicate its usefulness. They could be multiplied several times in number. Instead of doing this, however, I shall return to a consideration of the one aspect of vision, which I promised to treat in some detail. This is the capacity for intensity discrimination which is common to most photosensitive animals.

V. INTENSITY DISCRIMINATION

In our daily experience we constantly discriminate between bright and dim surfaces, and use this information in judging form and distance. How is this discrimination brought about? How in general do animals perceive intensity? This is a problem which has puzzled biologists for many years because of its importance in the relation between or-

[7] Hecht, S., The influence of temperature on the photosensory latent period, J. Gen. Physiol., *11*, p. 649; 1927–28.

ganism and environment, and between one part of an organism and another.

One phase of it has had a fascinating history culminating in what is currently known as the Weber-Fechner law. Weber[8] had found with the perception of weights that the minimum increase in weight which is just perceptible is roughly proportional to the weight already present. Calling ΔI the just perceptible increase of I, he believed to have found that $\Delta I/I$ is constant. In ordinary language this states that intensity perception is relative and not absolute. Fechner[9] later supposed that this ratio corresponds to a unit in sensation ΔS. He then integrated the relation between ΔS and $\Delta I/I$ and formulated the celebrated psychophysical law that the sensation produced is proportional to the logarithm of the intensity of the stimulus. This has been generalized to such an extent that when the physiological effect of a physical or chemical agent is proportional to the logarithm of its intensity, this relationship is referred to as the Weber-Fechner effect. As a result, many efforts have been made to find a basis for the Weber-Fechner law.

After the hypothetical sensory system just described had been formulated, it therefore seemed necessary to find out what the basis of the Weber-Fechner law is in terms of it. Before doing this, however, we investigated experimentally the intensity discrimination of certain animals. Our measurements, to our surprise, showed that $\Delta I/I$ is not constant.[10] Instead it varies in a specific way. At low illuminations the ratio is large; as the intensity increases the ratio becomes smaller; and finally at very high intensities it becomes larger again.

A study of the literature of the Weber-Fechner law revealed a most interesting story of scientific development. The Weber-Fechner law belongs to that class of generalization which, on account of its apparent reasonableness, becomes absorbed in the body of scientific knowledge and is held tenaciously as general truth, even though it represents only an extremely circumscribed portion of reality. The Weber-Fechner law in particular is so hardy a belief that it has had to be upset regularly every few years.

[8] Weber, E. H., De pulsu, resorptione, auditu et tactu annotationes anatomicae et physiologicae, Leipsic, 1834. Author's summary: Ueber den Tastsinn, Arch. Anat. u. Physiol., p. 152; 1835.

[9] Fechner, G. T., Ueber ein wichtiges psychophysiches Grundgesetz und dessen Beziehung zur Schätzung der Sterngrössen, Abhandl. k. sächs. Ges. Wissensch. Math. Phys. Kl., *4*, p. 31; 1858, as published separately; *4*, p. 455; 1859, as published in bound volume.

[10] Hecht, S., Intensity discrimination and the stationary state, J. Gen. Physiol., *6*, p. 355; 1923–24.

Weber[8] in 1834 described $\Delta I/I$ as constant for weights;—but it was in 1858 that Fechner[9] thought he demonstrated its constancy for vision. It was almost immediately shown to be incorrect by Helmholtz[11] who found that $\Delta I/I$ is not constant. Within five years it was reinvestigated by Aubert[12] who showed conclusively that $\Delta I/I$ is not constant for vision, because it varies from 1/3 at low intensities to 1/146 at high intensities. But the Weber-Fechner Law had been

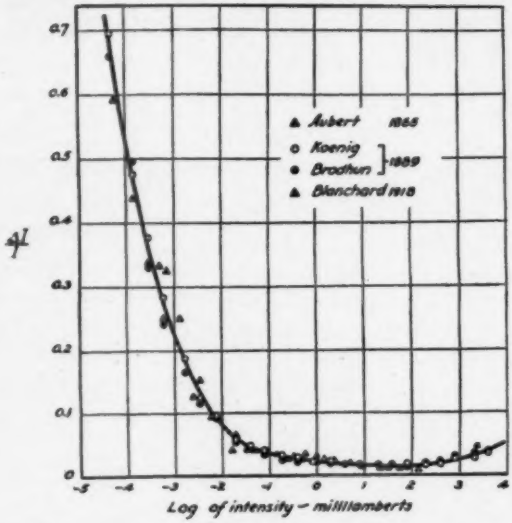

FIG. 7. *Intensity discrimination over the total illumination range visible to the eye. Blanchard's data are given in their original units: millilamberts. Koenig and Brodhun's intensities have been divided by 250 in order to convert them into millilamberts. Similarly Aubert's intensities have been divided by 10,000. It is apparent that these three groups of experimenters, working many years apart and independently, have arrived at essentially the same results, and that these results do not conform to the Weber-Fechner law.*

launched on its career and continued to be enthusiastically advanced by Fechner and others. However, the ratio $\Delta I/I$ was again investigated by Koenig and Brodhun[13] some twenty years later in a magnificent piece of experimental research. In this they showed that over a very

[11] Helmholtz, H., Handbuch der physiologischen Optik, Hamburg and Leipzig, 1st edition, 1866.

[12] Aubert, A., Physiologie der Netzhaut, Breslau, 1865.

[13] Koenig, A., and Brodhun, E., Experimentelle Untersuchungen über die psychophysische Fundamentalformel in Bezug auf den Gesichtssinn, Sitzungsber. Akad. Wissensch., p. 641; 1889, reprinted in Koenig, A., Gesammelte Abhandlungen, Leipzig, p. 135; 1903.

small range of intensities $\Delta I/I$ may be considered constant; but that viewed as a continuous physiological phenomenon, $\Delta I/I$ decreased steadily as the intensity increased up to a certain point, beyond which $\Delta I/I$ increased. Aubert's experiments, the measurements of Koenig and Brodhun and the recent work by Blanchard[14] all corroborate one another, and though made at intervals over half a century give identical results with the human eye (Fig. 7). Our own experiments with the clam show $\Delta I/I$ to have exactly the same type of behavior. By an inversion therefore, the problem of intensity discrimination is no longer a matter of explaining why $\Delta I/I$ is constant, but rather why it varies as it does.

VI. STATIONARY STATE

Consider what such measurements mean in terms of the photosensory system previously suggested. Let intensity I shine on an animal such as the clam. The light reaction $S \rightarrow P+A$ will proceed with a velocity

$$\frac{dx}{dt} = k_1 I(a - x_1)$$

where $(a\text{-}x)$ is the concentration of S, and x that of P and A. The reverse reaction, $S \leftarrow P+A$ will proceed as soon as some P and A are formed and will proceed according to

$$-\frac{dx}{dt} = k_2 x_1^2.$$

If the light continues to shine, a stationary state will be reached in which these two opposing velocities will be equal. The equation

$$KI = \frac{x_1^2}{a - x_1}$$

will describe this state, where $K = k_1/k_2$. If the illumination is now changed to $I+\Delta I$, then the stationary state

$$K(I+\Delta I) = \frac{x_2^2}{a - x_2}$$

will describe the concentrations of S, P and A.

The photochemical effect produced by the addition of ΔI is the increase in concentration equal to $x_2 - x_1$. We have found in other studies

[14] Blanchard, J., The brightness sensibility of the retina, Phys. Rev., *11*, series 2, p. 81; 1918.

with these animals that in order to stimulate them a definite amount of S must be decomposed. The change from I to $I+\Delta I$ represents such a stimulation. Therefore the change in concentration of S, or x_2-x_1, should be constant regardless of the curious way in which ΔI and I are related to each other. The computations[10] in terms of these equations are straightforward, involving only one constant, K. They show that x_2-x_1 is constant even though for the clam $\Delta I/I$ may vary pretty much as in the eye.

The sensory system in the human eye is much like that of the clam. It would be perhaps more accurate to say like that of two clams, because the clam possesses one type of photosensitive cell, whereas the eye has two kinds,—the rods and the cones. In dark adaptation these two systems behave similarly but independently. The same is true in intensity discrimination.

Koenig and Brodhun's measurements are made at 24 points within the whole range of intensities over which the eye is capable of working. At low intensities discrimination is a function of the rods; at high illuminations it is a function of the cones. We have calculated[15] the data in terms of the above equation for the stationary state. The lowest 7 intensities at which discrimination was measured give constant values of the increment in concentration, x_2-x_1 equal to an average of 1.56. They are determined by the rods. The remaining 17 intensities are mediated by the cones and they show x_2-x_1 to be of a different order of magnitude and equal to an average of 0.21. The point of transition from rods to cones determined in this way is at an intensity which from other independent experiments is known to correspond to the transfer of function from the dim vision of the rods to the color vision of the cones.

The conclusion from these measurements and computations seems to be that for the photosensory elements to discriminate between one intensity and the next perceptible one, the transition from one to the other must involve the decomposition of a constant amount of photosensitive material.

VII. ALL OR NOTHING LAW

Historically the idea behind the Weber-Fechner law was an effort to describe the nature of intensity recognition in terms of intensity

[15] Hecht, S., The visual discrimination of intensity and the Weber-Fechner Law, J. Gen. Physiol., 7, p. 235; 1924–25.

discrimination. It obviously failed to accomplish this because it was based on data which do not describe intensity discrimination correctly. However the failure of the psychophysical law is deeper than this. It omitted recognition of a fundamentally significant characteristic of intensity perception, namely its discontinuity. Starting with a given intensity, there is always a definite increase or decrease in this intensity which must be made before it can be recognized with certainty as different. In terms of our ideas each of these just perceptible steps represents a constant, unitary increase in the quantity of photosensitive material decomposed in the visual cells. It is very important to consider the nature and consequences of these unitary increases.

A naive way would be to suppose that a greater concentration of decomposition products in the sense cell represents a greater chemical or electrical effect on the nerve which is then passed on to the proper centers and finally to an effector like a muscle or a gland. We know however that nerve and muscle do not behave quite so simply; and recently Adrian[16] has shown us that sense organs do not behave so simply either. The impulse along a single nerve fiber is constant in magnitude regardless of the size of the stimulus. The contraction of a single muscle fiber is of constant magnitude regardless of stimulus. Nerve and muscle behave like quanta of energy in physics; they are either all or nothing. Just as the naive conception of intensity has disappeared in physics and been replaced by number so indeed is it disappearing in biology. A light that is more intense than another is merely emitting more quanta per unit time and space than another. Can we apply a similar type of idea in the perception of intensity in biological systems?

There are two ways in which such an idea may be applied, and both of them have been suggested. The oldest is that of Lucas and was considered for muscle. Lucas[17] found experimentally that as the stimulus to a muscle increased gradually, its height of contraction increased in a series of discrete steps the number of which corresponds with the total number of individual muscle fibers in the muscle. Intensity in muscle is therefore registered by the number of elements which are functional.

[16] Adrian, E. D., The impulses produced by sensory nerve-endings. Part 4. Impulses from Pain Receptors, Jour. Physiol., *62*, p. 33; 1926.

[17] Lucas, K., The "all or none" contraction of the amphibian skeletal muscle fibre, J. Physiol., *38*, p. 113; 1908–09.

When it was shown that the nerve impulse is all-or-nothing as well,[18] another idea was suggested by Forbes.[19] This is that intensity is determined by the number of impulses which proceed over a single nerve fiber in a given time, in other words that the frequency of the impulses determines intensity. In fact the beautiful researches of Adrian[20] have shown beyond a doubt that the frequency in a single nerve fiber actually does increase with intensity; and moreover it can determine the height of contraction in the attached muscle.

Which of these two aspects of number applies to the intensity recognition of the photosensory system? Is it number of unit structures, or is it number of impulses in a single structure per unit time? One thing is certain. Whether we give it first place in vision or not, frequency is a factor in intensity perception. This is true as Adrian's work has shown experimentally. The problem really is, first, whether number of structures enters at all as a factor; and if it does, second, how the concept of frequency of impulses in a single element and the concept of number of elements, work together to give intensity discrimination and perception.

On the face of it, it is difficult to consider frequency alone as the basis of intensity discrimination. Frequency is a continuous function because time is continuous. But it is a fundamental property of intensity recognition that it is discontinuous in vision as well as in muscle. Therefore we must turn to the idea involving number of elements. This idea has long been in the air,[19, 21, 22], but its quantitative implications and demonstration have not been made until recently.[23] The matter can actually be tested experimentally; and fortunately the experiments have been to hand for about thirty years. They concern the relation between the intensity of illumination and the visual acuity of the human eye.

[18] Adrian, E. D., The all-or-none principle in nerve, J. Physiol., *47*, p. 460; 1913–14.

[19] Forbes, A., and Gregg, A., Electrical studies in mammalian reflexes. II. The correlation between strength of stimuli and the direct and reflex nerve response, Am. J. Physiol., *39*, p. 172; 1915–16.

[20] Adrian, E. D., and Bronk, D. W., The discharge of impulses in motor nerve fibres. Part I. Impulses in single fibres of the phrenic nerve, Jour. Physiol., *66*, p. 81; 1928.

[21] Brown, T. G., On the question of fractional activity ("all or none" phenomenon) in mammalian reflex phenomena, Proc. Roy. Soc. London, Series B, *87*, p. 132; 1913–14.

[22] Lasareff, P., Über die Empfindung der Lichtintensität beim peripheren Sehen auf Grund der Ionentheorie, Arch. ges. Physiol., *199*, p. 290; 1923.

[23] Hecht, S., The relation between visual acuity and illumination, J. Gen. Physiol., *11*, p. 255; 1928.

VIII. VISUAL ACUITY AND ILLUMINATION

It is common experience that the fineness of detail which we can distinguish with our eyes varies with the intensity of illumination. At low illuminations we cannot read the fine print which is easily legible at higher illuminations. Our capacity for visual resolution of detail is called visual acuity and can be measured accurately by a variety of means. The relation of visual acuity to illumination has been known in a roughly quantitative way for about 150 years; but it was only 30 years ago that it was most carefully measured by Koenig[24] in such

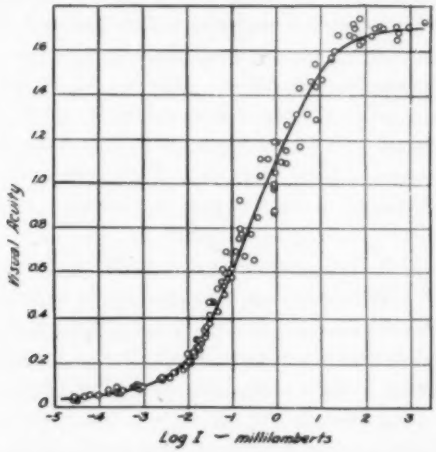

FIG. 8. *Relation between visual acuity and illumination. Koenig's original intensities have been multiplied by 0.072 to convert them into millilamberts. The curve is a theoretical one, derived as explained in the text.*

detail that his results have become classic (Fig. 8). We know from these data that visual acuity varies with the logarithm of the intensity in a specific way.

This is an extraordinary situation when one tries to realize its implications. Visual acuity is of course the resolving power of the retina. The data then show that this resolving power gradually increases up to nearly a hundred times its initial value as the illumination is increased. Now we know that the resolving power of a surface composed of discrete, independent, receiving elements,—like the photographic

[24] Koenig, A., Die Abhängigkeit der Sehschärfe von der Beleuchtungsintensität, Sitzungsber. k. Akad. Wissensch., p. 559; 1897.

plate for example,—varies with the number of such elements in a given area; or to be more specific with their distance apart. The retina is such a surface, because it is composed of discrete elements, the rods and the cones. The data of visual acuity must therefore mean that at low illuminations there are fewer rods and cones present in the retina than at higher illuminations; certainly it must mean that the distance between the centers of the receiving elements varies inversely with the illumination.

But we know that this is nonsense anatomically, because the rods and cones are fixed in the retina; they do not separate and come together, nor do they increase and decrease in number. We must therefore assume these differences functionally. The rods and cones represent

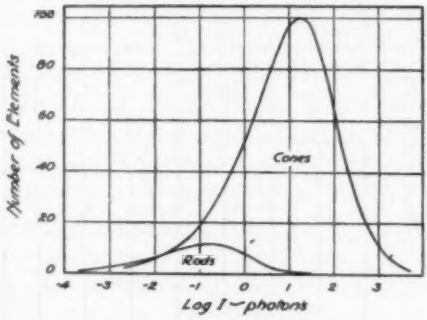

FIG. 9. *Distribution of thresholds of rods and cones. The intensities are in photons, representing retinal illumination, and have been derived by correcting the outside illuminations given in Fig. 8 by the corresponding pupil areas. The two curves are identical in form, but different in position on the abscissas and in size of ordinates.*

two pretty large populations of cells. We must therefore suppose that they do not all have identically the same threshold, but that they vary in this respect much as other populations do. At low illuminations a few elements will be functional because the intensity is above their particular threshold. And as the intensity increases, more and more cells will become functional because the intensities will correspond to the thresholds of more and more elements. Since the thresholds are distributed at random, the distance between functional elements will decrease, and visual acuity will increase.

How can we describe quantitatively the relation between visual acuity and illumination in terms of such an idea? The simplest way is to ascertain what type of population distribution of thresholds it is

necessary to assume in order to describe the data. We have seen previously that the rods and cones are two independently functional systems which must be treated separately. We may then draw two curves (Fig. 9) which represent the two populations in relation to their thresholds. It is apparent that the curves look like any common distribution curves used by statisticians. These curves are differential curves and give the number of elements whose specific thresholds corresponds to a given intensity. What we need are integral curves which summate the individual thresholds and give us the total number

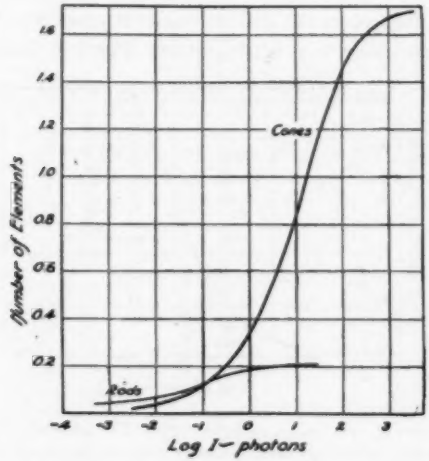

FIG. 10. *Statistical distribution of the sensibility of rods and cones. These curves are the integrals of those in Fig. 9, and give the relative number of elements per unit retinal distance functional at any intensity. The curves may be described by the common Gram series of the statisticians. However, the equation here used is* $KI = x^3/(a-x)$ *where K and a have different values for the two curves. The ordinates read directly in visual acuity* (x).

of elements functional at a given intensity. These can be supplied by the usual methods; and these integral distribution curves (Fig. 10) correspond accurately with the data of visual acuity.

At low illuminations a few rods are functional. They are therefore far apart and visual acuity is low. As the illumination increases the number of functional rods increases; they are therefore closer together, and visual acuity increases. At a certain intensity, the cones begin to function and since the rate at which they come into play is more rapid than the rods, the cones take over visual acuity. As they gradually

increase in the number functioning, visual acuity increases, until a point is reached when they are all functional and further increase in intensity produces no increase in visual acuity.

IX. INTENSITY AND NUMBER

The relation of all this to intensity perception and discrimination is almost obvious. Here we have completely independent evidence of the fact that differences in intensity are associated with differences in the number of elements functional in the retina. However, for us to link intensity discrimination with this variation in number we need a closer consideration of visual acuity and intensity discrimination. On the basis of the same intensity discrimination data which we have used here, Koenig found that it is possible to recognize 572 discrete steps in intensity over the complete range visible to the eye. The first 30 of these steps are mediated by the rods; the remainder, 542 by the cones. If the recognition of a minimal intensity difference ΔI represents a change from n to $n+1$ or $n-1$ in the number of cones functional in a unit retinal area, then the minimal retinal area in the fovea, where the cones are, must contain 542 cones. Only in this way can each step in intensity discrimination correspond to an increase or a decrease in the number of functional cones in a unit area.

If visual acuity and intensity discrimination are manifestations of the same mechanism, such a minimal retinal area should be able to mediate all the visual acuities, from the lowest to the highest. Such an area will have for its linear dimensions the retinal distance between two just perceptible contours corresponding to the lowest visual acuity. The retinal distances for all other visual acuities will obviously fall within this distance. From Koenig's data (Fig. 8) the lowest visual acuity is 0.03 units. This corresponds to a visual angle of $44'$, and to a retinal distance 0.2 mm. The resulting square area is 0.04 sq. mm. The fovea contains 13 500 cones per sq. mm.[25] This minimal visual acuity area therefore contains 540 cones, which is the same number as that derived from measurements of intensity discrimination.

Another relation between visual acuity and intensity discrimination can be shown as follows. The first 30 steps in intensity discrimination are made by the rods. It was shown that this corresponds to just about half the full range of function of the rods. The same is apparent when

[25] Helmholtz, H., Handbuch der Physiologischen Optik, 2nd edition, Hamburg and Leipzig, 1896.

the rods give up the determination of visual acuity to the cones. The full possible range of rod activity in intensity discrimination is thus 60 steps. The cones have 542 steps. This is a ratio of 1:9. Note the same ratio in visual acuities. The maximum rod visual acuity is 0.21; the maximum cone visual acuity is 1.71. This is a ratio of 1:8+.

However, it can be shown even more directly that visual acuity and intensity discrimination are two manifestations of the same mechanism when we consider the basis for the population curves describing visual acuity and illumination. We have called these statistical population curves; and so they are, because they look like such curves and can be described by the usual statistical equations. Actually however, they are curves which describe the concentration, x, of the photo-

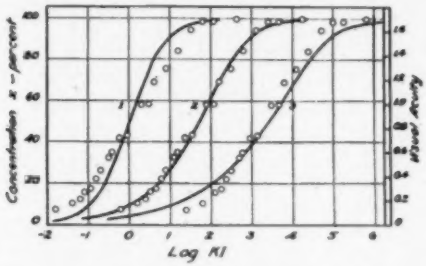

FIG. 11. *This curve illustrates the relation of cone visual acuity to the stationary state equation* $KI=x^n/(a-x)$. *The visual acuity data are those of Koenig and are the averages of Fig. 8. The intensity is in photons. When* $n=1$, *the "dark" reaction is considered unimolecular; when* $n=2$ *it is bimolecular; when* $n=3$, *it is trimolecular. It is apparent that the curve when* $n=2$ *is the only one that describes the data adequately, and thus furnishes independent evidence to the effect that dark adaptation is bimolecular.*

chemical decomposition products P and A at the stationary state produced by any intensity of illumination (Fig. 11). The integral curves are nothing but the graphs for the stationary state equation

$$KI=\frac{x^2}{a-x}$$

which we used for intensity discrimination.

It is important to consider this more closely. We have assumed that the retinal elements vary in threshold on the general principle that populations vary in this way. But we gave no basis for this variation in threshold; moreover we never defined its exact location and status. Let us assume that the initial concentration of photosensitive

substance S is the same in all the rods, and in all the cones; but of course not the same in cones and rods. But let us assume that the concentration of decomposition products necessary to discharge a cell varies from cell to cell. Since there is no reason for selecting any given concentration it follows from pure chance that each concentration will have the same number of cells whose discharge thresholds it will represent. In other words, for number of cells in the population curve one can substitute concentration of P and A and the curves become our photochemical representation of intensity discrimination. The same photochemical mechanism therefore underlies both properties, and we must conclude that intensity recognition as well as visual acuity is determined by the number of retinal elements functional in a given retinal area.

X. NUMBER AND FREQUENCY

What then becomes of the frequency of discharge of a given cell? This surely exists in the retina, and undoubtedly has a function. I believe we can fit it into our scheme; in fact it is essential to our notions if the story of intensity discrimination is to be complete.

We have repeatedly emphasized the fact that intensity recognition is discontinuous. With this discreteness is however associated a curious property. Let us place intensity I on one side of a photometric field and the just next perceptible intensity $I+\Delta I$ on the other side of the field. According to our ideas I corresponds to n cones per unit area and $I+\Delta I$ to $n+1$ cones. What happens if we were to put an intensity midway between these two, say $I+\Delta I/2$, on one side of the field? How many cones would this correspond to? Obviously to n again. Now what is the next just perceptible intensity to this? Experiment shows that it certainly is not $I+\Delta I$ which presumably corresponds to $n+1$ cones. The next perceptibly different intensity is very nearly $I+\Delta I/2+\Delta I$. This seems absurd since if $I+\Delta I/2$ corresponds to n cones, then all that one should need to go to is $I+\Delta I$ previously known to correspond to $n+1$ cones.

The solution of this paradox lies in a recognition of the full implications of our photosensory model as it applies to frequency. The photic decomposition products P and A are by themselves not the agents which set off the nerve discharge. It is the products of the secondary latent period reaction which is in some way influenced, perhaps catalytically, by these photochemical products. The products of this secondary reaction are constantly being formed at a rate which

is proportional to the concentration of P and A formed by the light. Each cell has its specific threshold of discharge. But since these secondary products T are formed steadily each cell will discharge at a frequency which varies directly with concentration of P and A, and inversely with the threshold concentration.

Take any given cell. It will begin to function when the concentration of P and A corresponds to its discharge threshold. It will then discharge at regular intervals and the frequency of its discharge to the nerve will be minimal. As the intensity increases, this frequency will increase steadily. However, presently the threshold of the next most sensitive cell will be reached and it will begin to function at a given frequency which will also increase with intensity. Since we found that intensity discrimination corresponds to a definite increase in photochemical products, it must correspond to the addition of an element functioning at the same frequency as the last one. In other words intensity discrimination in this analysis, depends on a definite increase in the frequency of discharge of a series of related retinal elements, the increase being made by the addition of a new functional element. In this way may be harmonized the two paradoxical characteristics of intensity discrimination, first that intensity discrimination is discontinuous, and second, that there are no critical points in intensity but that the discontinuity may be made at any intensity.

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